Isospin conserving model and the resonance proton scattering on a thick target in inverse kinematics. The ^{9}He «puzzle»

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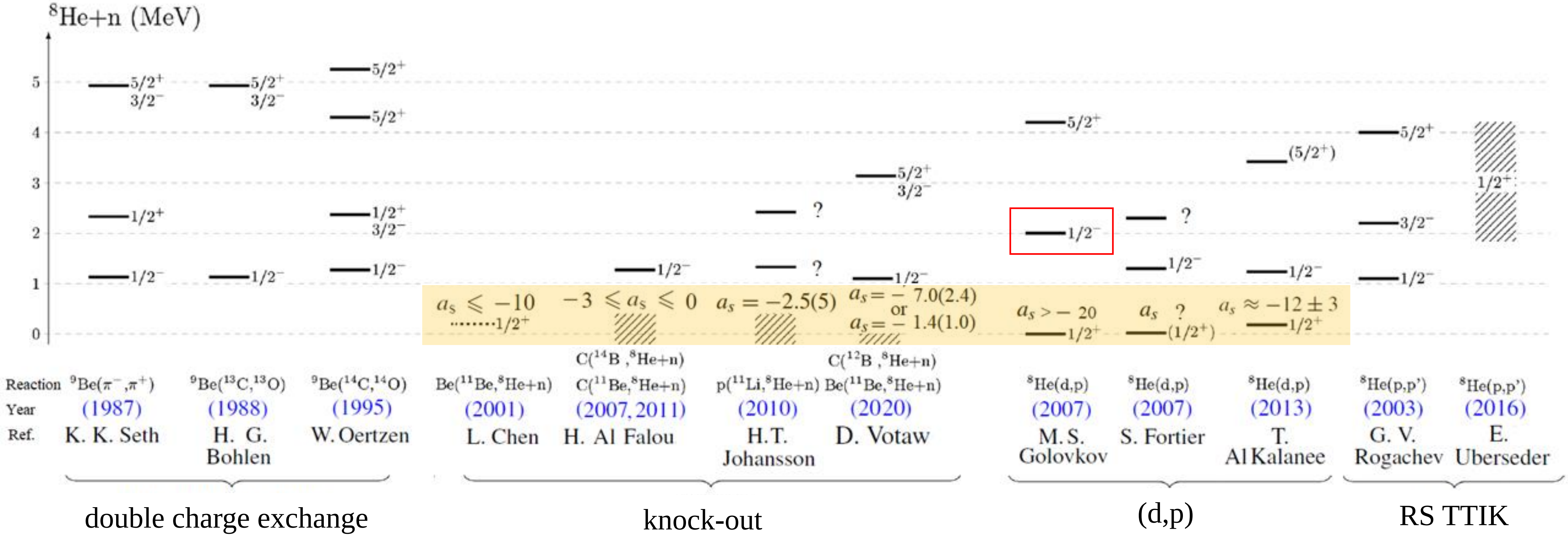
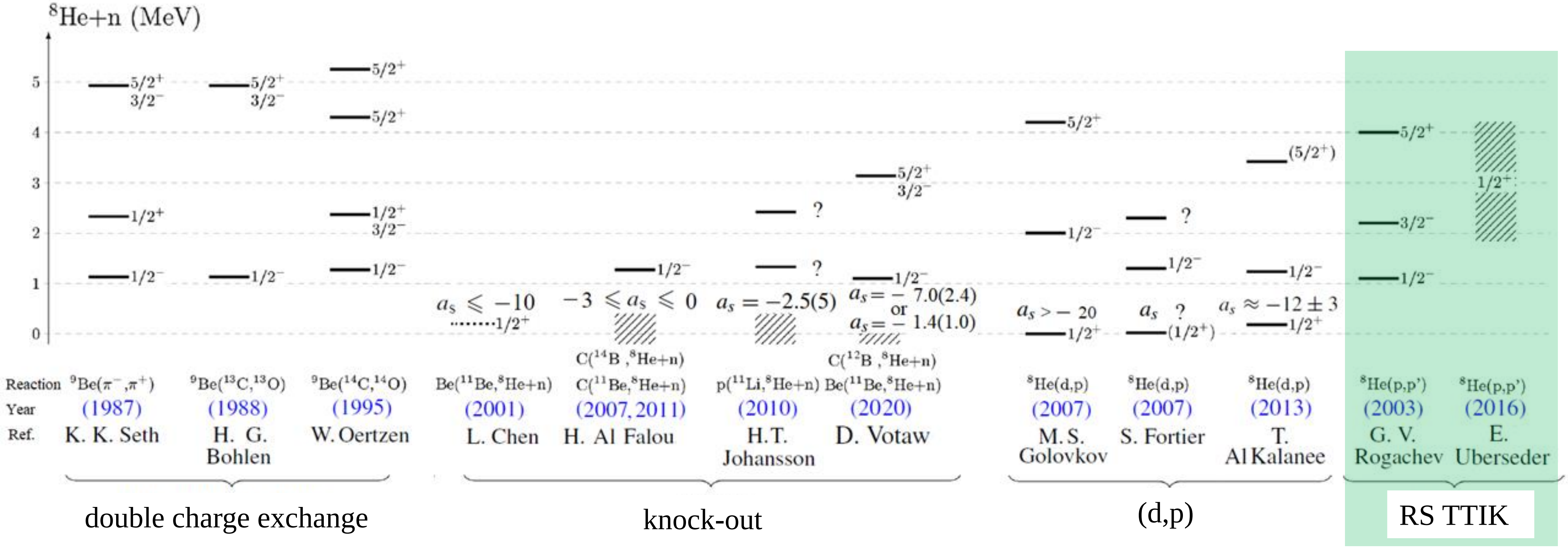
What do we know about the ^{9}He structure?



all scattering lengths a_s in fm

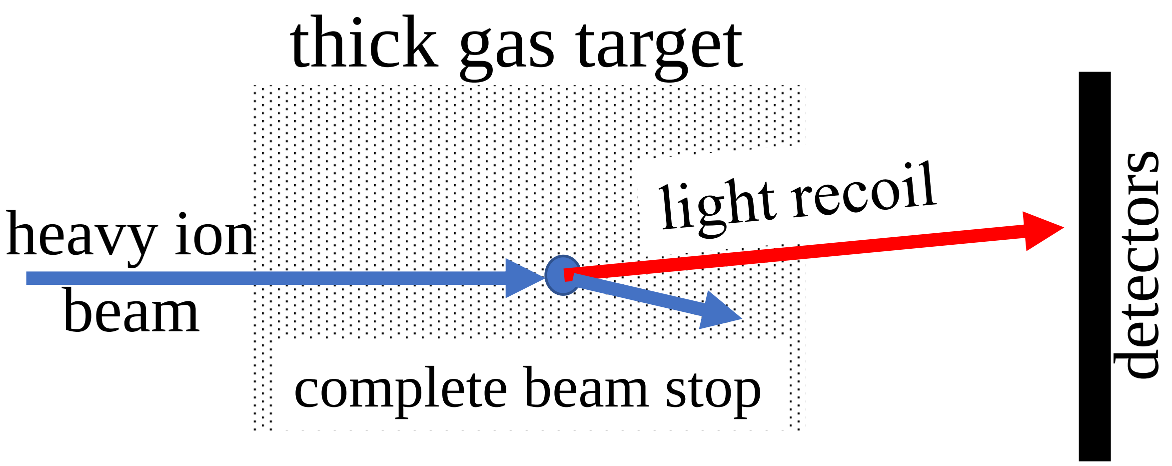
What do we know about the ^{9}He structure?



- ^{9}He G.S. is $s_{1/2}$ or $p_{1/2}$?
- $E_r(p_{1/2})$ = 1.1 MeV or $E_r(p_{1/2})$ = 2.0 MeV?

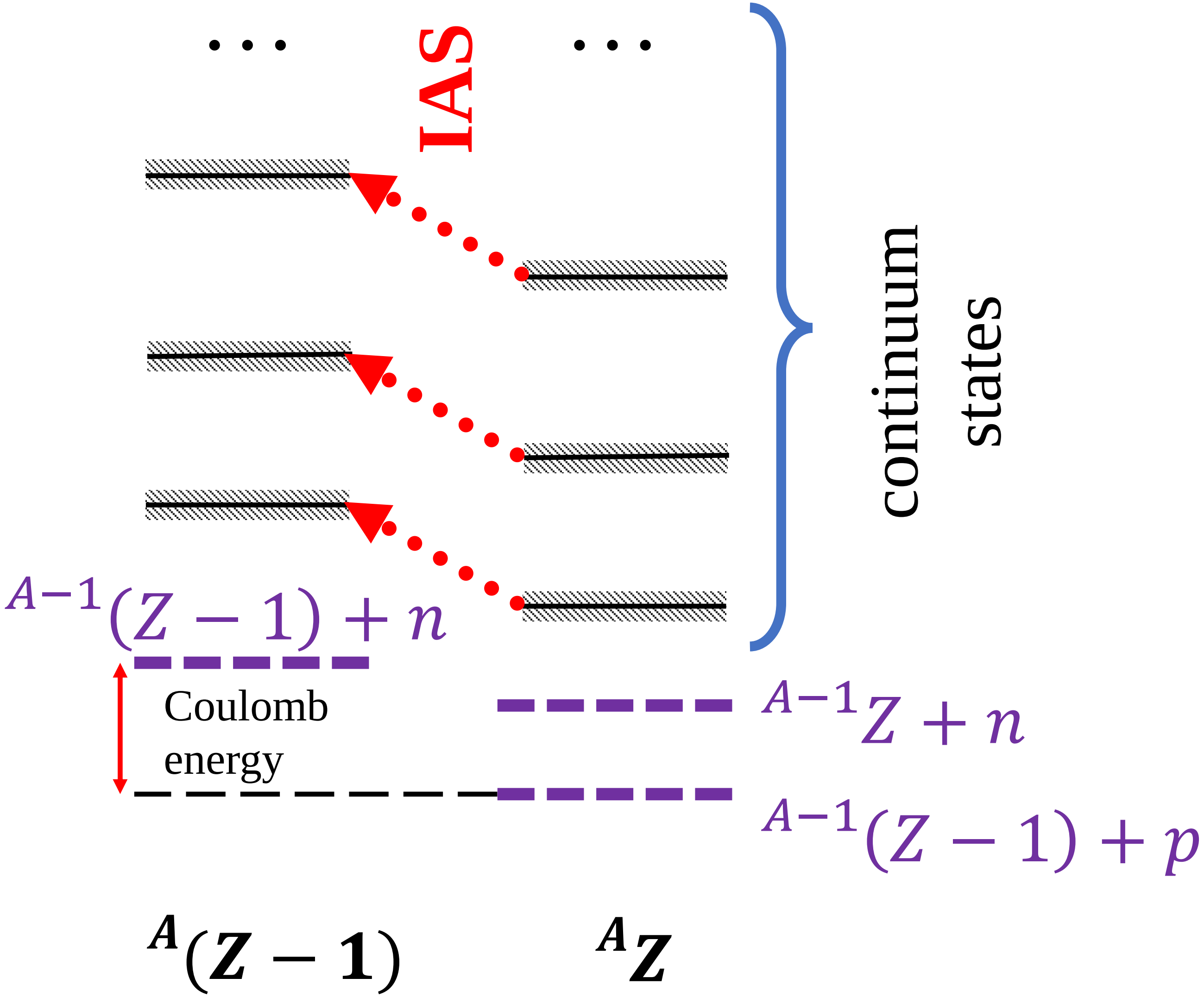
Resonance Proton Scattering on a thick target in inverse kinematics (TTIK)

- The thick target inverse kinematics (TTIK) method was proposed by V. Z. Goldberg and others about 35 years ago [1-4].
- This method can be used to study resonance reactions induced by exotic radioactive beams of low quality and intensity. The beam of heavy ions is slowed and stopped in a **thick** gas CH_4 target. The light recoils (protons) are detected from a scattering event.
- Thus, the measurement of a recoil particles energies provides for a continuous excitation function of elastic scattering.



[1] K. P. Artemov, O. P. Belyanin, A. L. Vetoshkin, R. Wolski, M. S. Golovkov, V. Z. Goldberg et al., Sov. J. Nucl. Phys. USSR 52, 408 (1990)
[2] V. Z. Goldberg, International Conference on Clustering Phenomena in Atoms and Nuclei (1991)
[3] V. Z. Goldberg et al., JETP Lett. 67, 1013 (1998).
[4] V. Z. Goldberg et al., Phys. Rev. Res. 2, 032036(R) (2020).

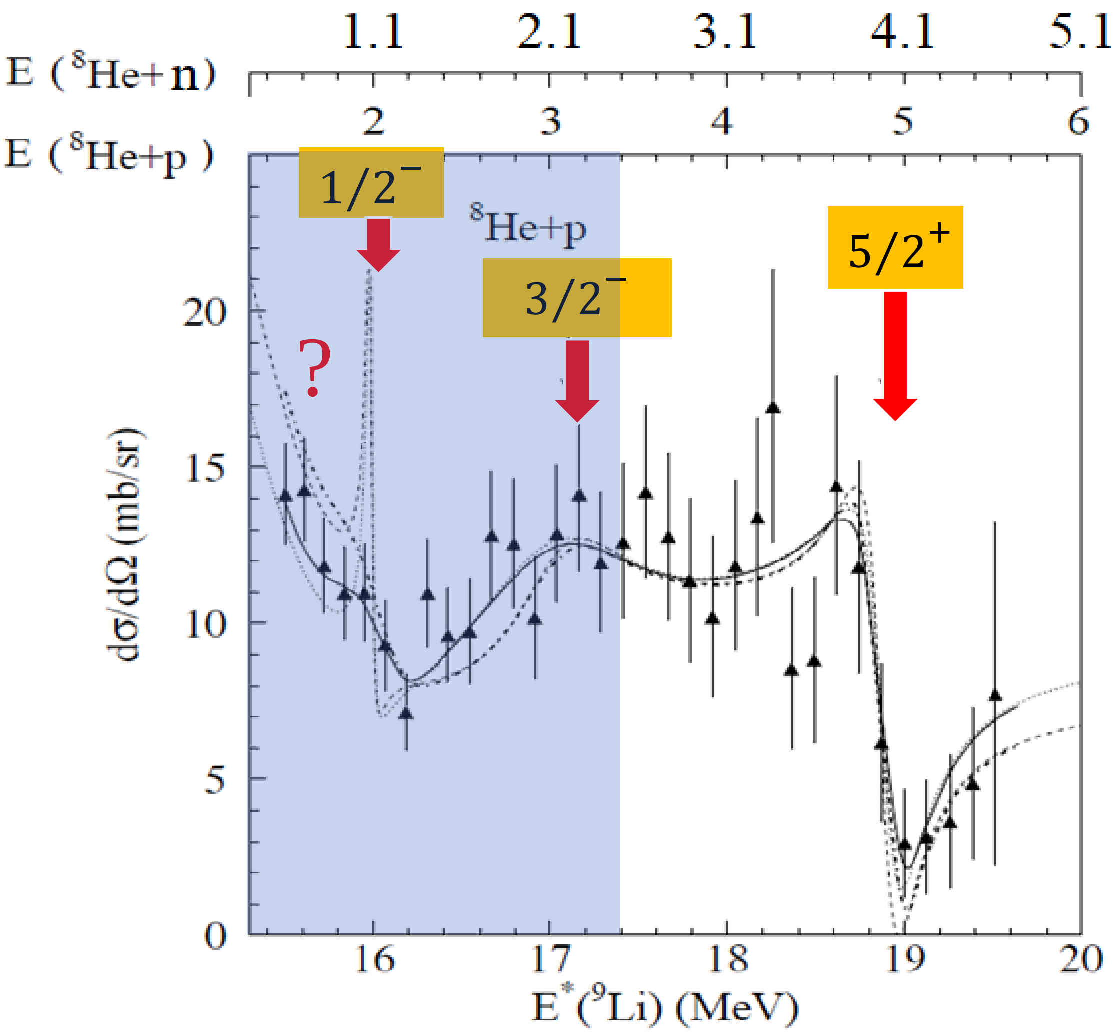
The study of isobaric analog states of neutron rich nuclei by TTIK method



- The application of the method is very natural for the proton continuum of proton-rich exotic nuclei, where the interpretation of elastic scattering results is straightforward and unique.
- The study of isobaric analog states of neutron rich nuclei by this method has been proposed by V. Z. Goldberg [5]. The method is based on studies of isobaric-analog states in the ^{A}Z+*p* scattering and use of the isospin symmetry concept to infer the ^{A}Z+*n* properties.

[5] V.Z. Goldberg, in ENAM98, Exotic Nuclei and Atomic Masses, edited by Bradley M. Sherrill, David J. Morrisey, and Cary N. Davids, AIP Conf. Proc. No. 455 p. 319. (1998)

Data [Rogachev 2003]

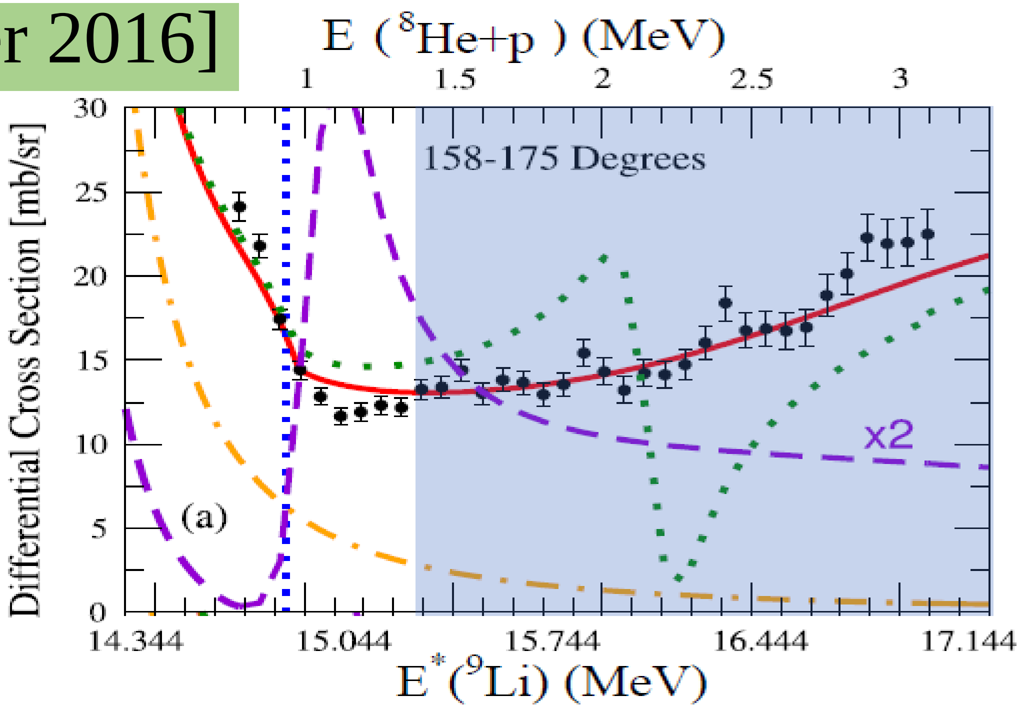


G. V. Rogachev et al., Phys. Rev. C 67, 041603 (2003).

Interpretation:

$T = 5/2$ ***resonances***

Data [Uberseder 2016]

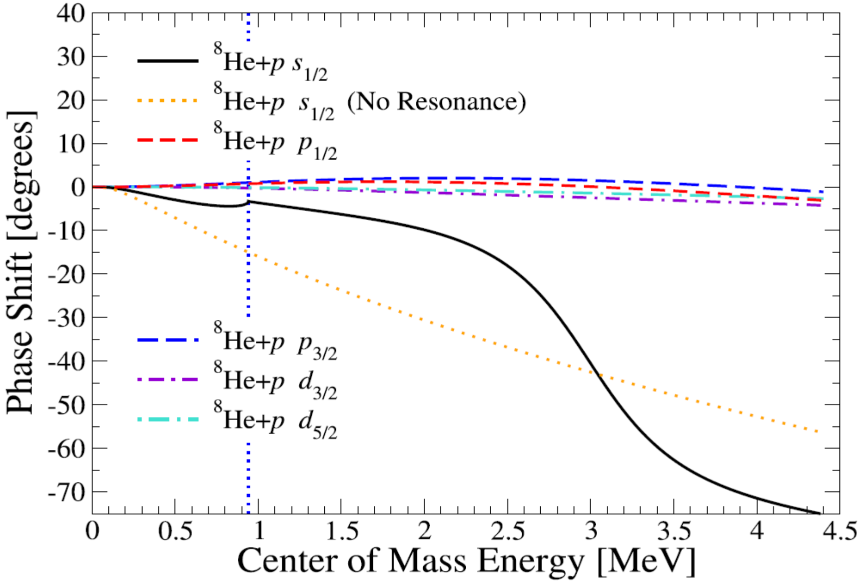


E. Uberseder et al., Phys. Lett. B 754, 323 (2016).

Interpretation:

$1/2^+$ resonance

$E_r \sim 3$ MeV



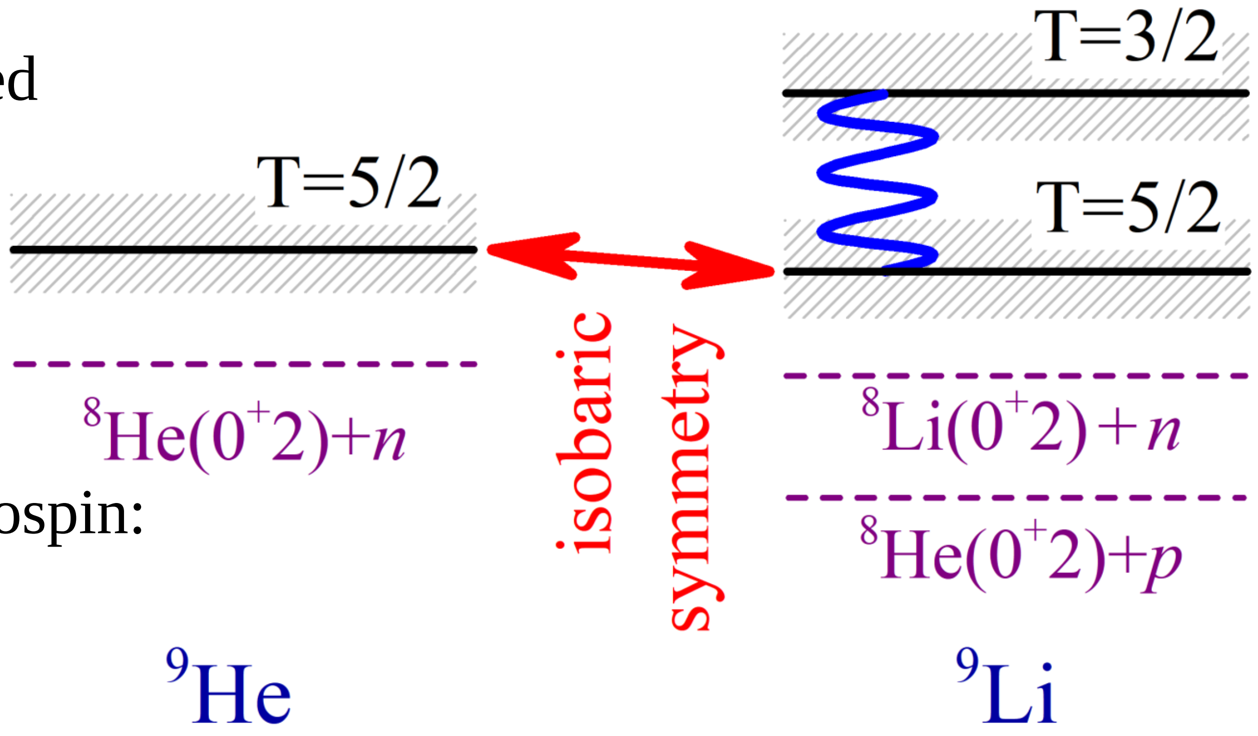
Isospin conserving model

M. S. Khirk, L. V. Grigorenko, D. E. Lanskoy and P. G. Sharov., Phys. Rev. C111, L051601(2025)

- Interaction between clusters can be represented as a sum of terms with definite isospin:

$$\hat{V} = V_{3/2}(r)\,\hat{P}_{3/2} + V_{5/2}(r)\,\hat{P}_{5/2}$$

fixes the spectrum of ^{9}He



- WF decomposition into states with definite isospin:

$$\Psi_{^{8}\text{He-}p} = \frac{1}{\sqrt{5}}|T = 5/2\rangle + \frac{2}{\sqrt{5}}|T = 3/2\rangle$$

$$\Psi_{^{8}\text{Li}^{*}\text{-}n} = \frac{2}{\sqrt{5}}|T = 5/2\rangle - \frac{1}{\sqrt{5}}|T = 3/2\rangle$$

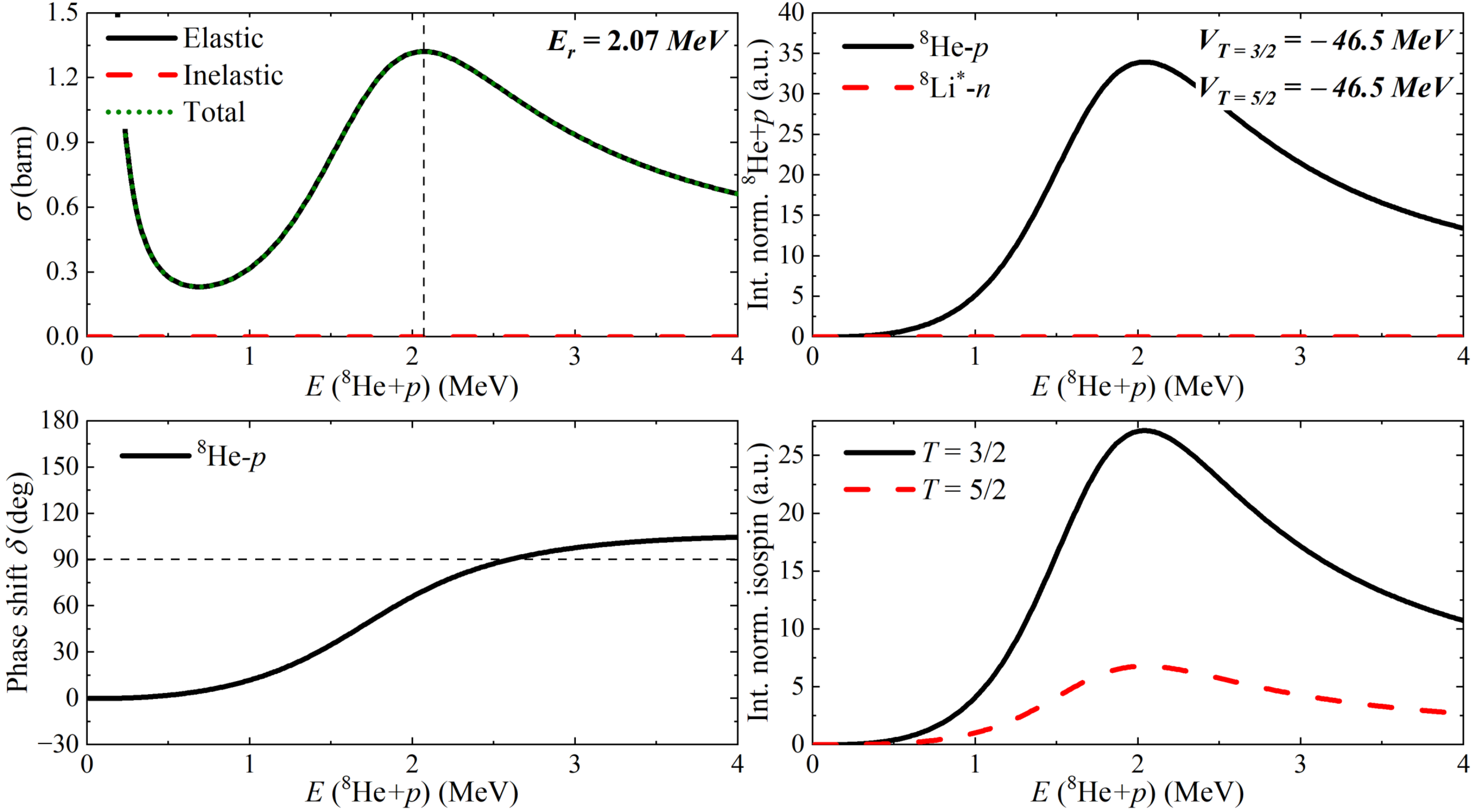
$V_{3/2} \equiv V_{5/2}$ decoupled channel case (strong isospin mixing)

- System of coupled Schrödinger equations:

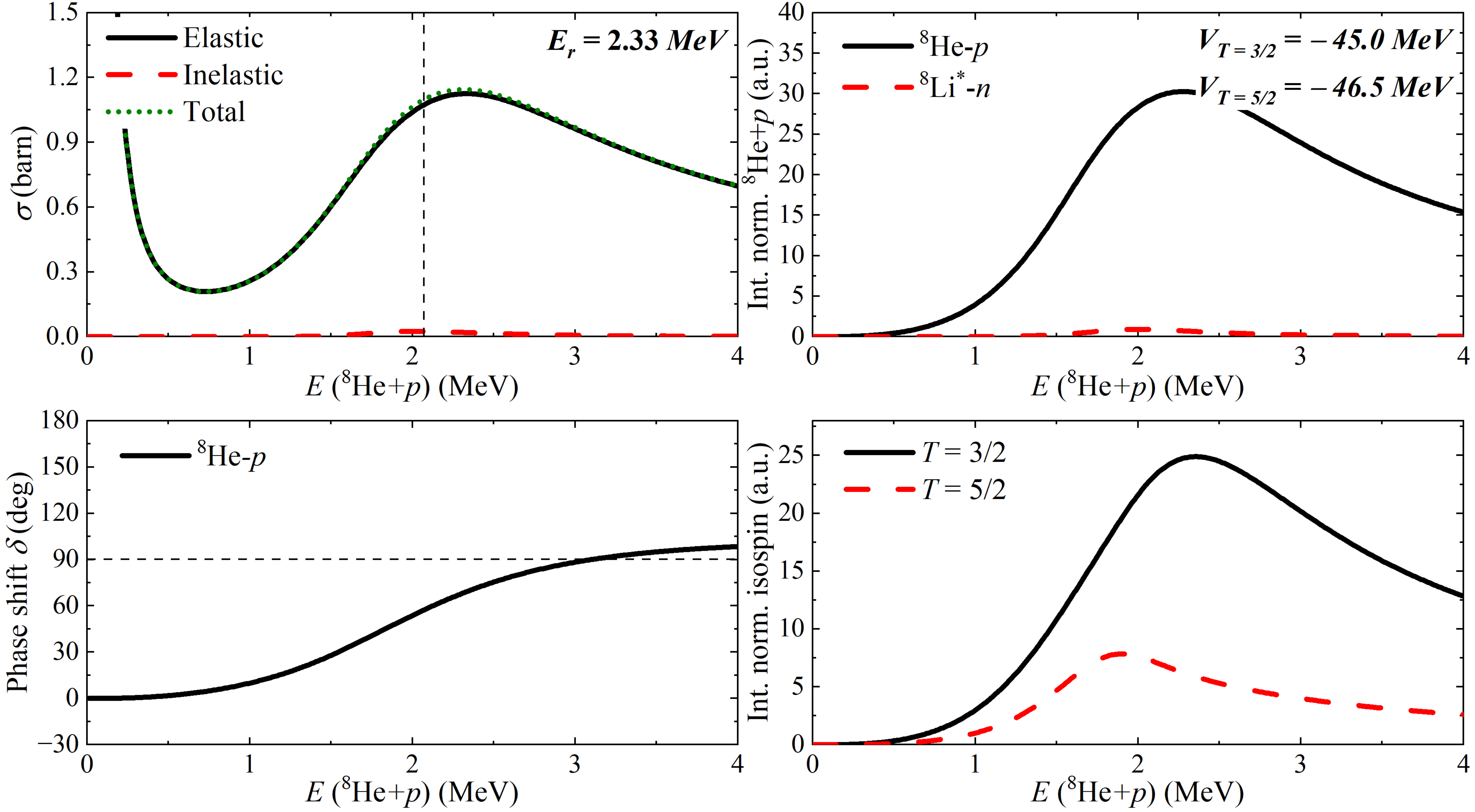
$$\begin{cases} \left(T - E + V_{coul} + \frac{4V_{3/2}+V_{5/2}}{5}\right)\Psi_{^{8}\text{He-}p} + \frac{2}{5}\left(V_{5/2} - V_{3/2}\right)\Psi_{^{8}\text{Li-}n} = 0 \\ \left(T - (E - 0.94) + \frac{V_{3/2}+4V_{5/2}}{5}\right)\Psi_{^{8}\text{Li-}n} + \frac{2}{5}\left(V_{5/2} - V_{3/2}\right)\Psi_{^{8}\text{He-}p} = 0 \end{cases}$$

^{9}He E_r ($p_{1/2}$) = 1.1 MeV

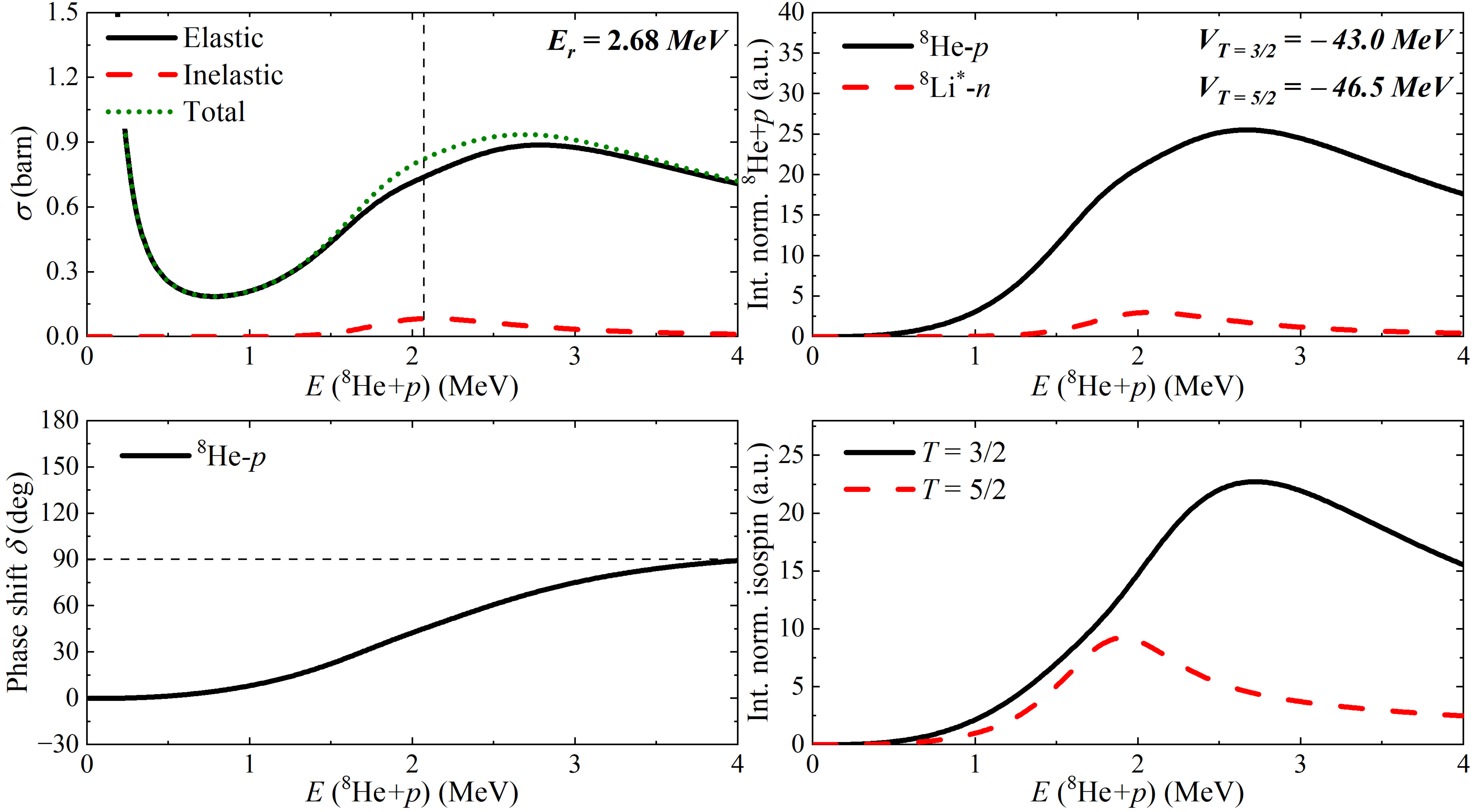
$V_{3/2}$ depth variation



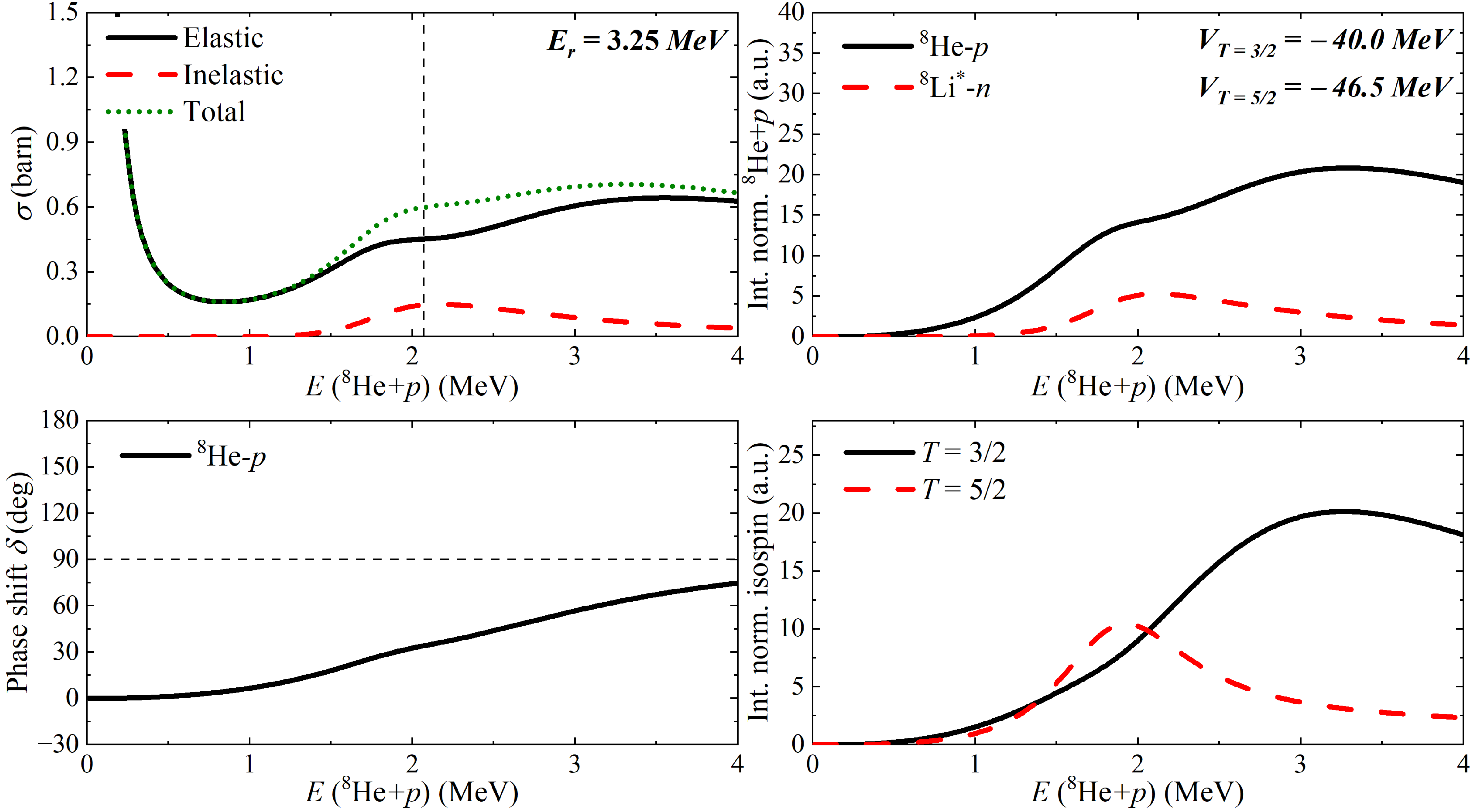
Elastic
Inelastic
Total
E_r = 2.07 MeV
σ (barn)
E (⁸He+p) (MeV)
⁸He-p
⁸Li*-n
$V_{T=3/2}$ = −46.5 MeV
$V_{T=5/2}$ = −46.5 MeV
Int. norm. ⁸He+p (a.u.)
E (⁸He+p) (MeV)
⁸He-p
Phase shift δ (deg)
E (⁸He+p) (MeV)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)
E (⁸He+p) (MeV)



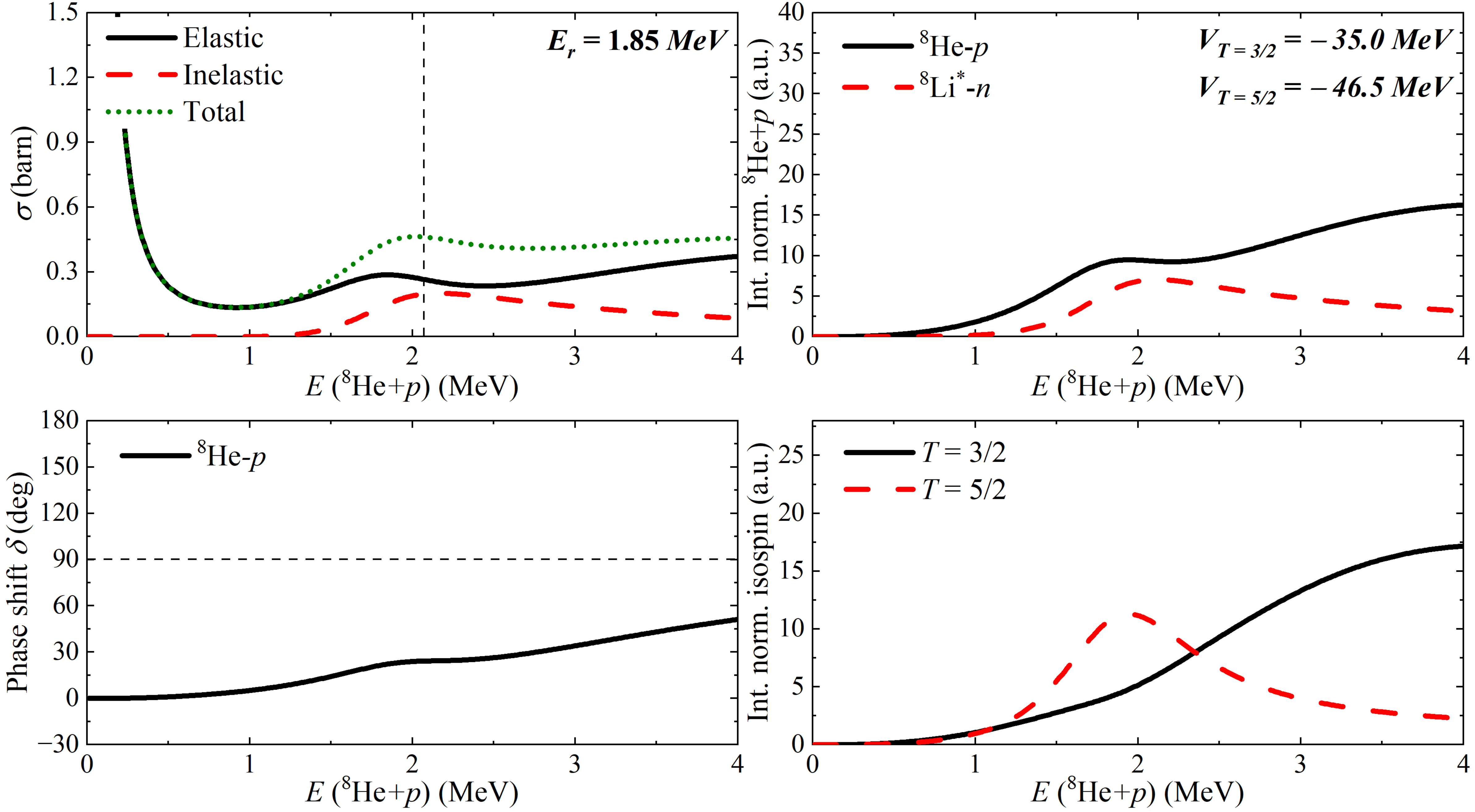
Elastic
Inelastic
Total
E_r = 2.33 MeV
σ (barn)
E (^{8}He+p) (MeV)
^{8}He-p
^{8}Li*-n
$V_{T=3/2}$ = −45.0 MeV
$V_{T=5/2}$ = −46.5 MeV
Int. norm. ^{8}He+p (a.u.)
Phase shift δ (deg)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)



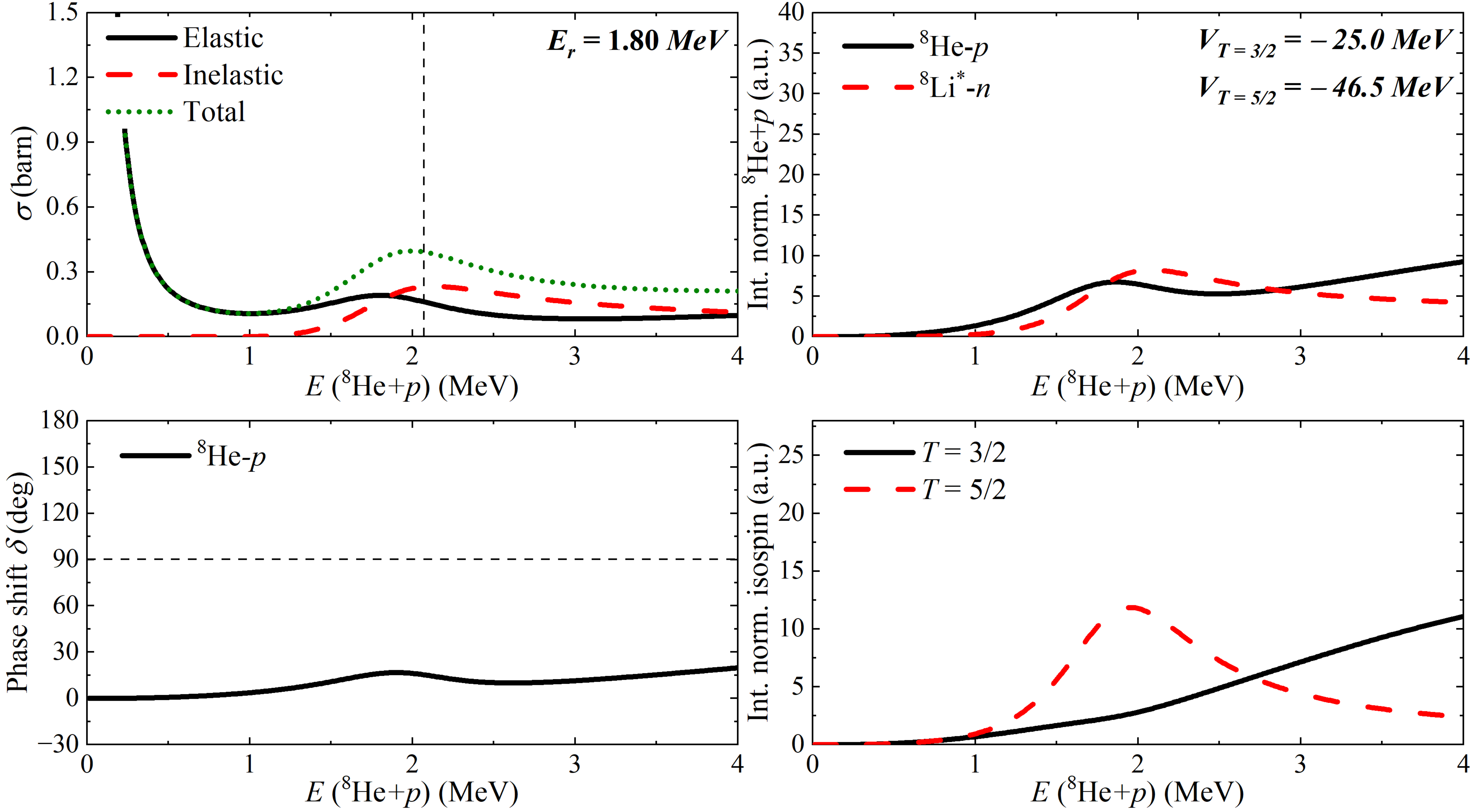
Elastic
Inelastic
Total
E_r = 2.68 MeV
σ (barn)
E (⁸He+p) (MeV)
⁸He-p
⁸Li*-n
$V_{T=3/2}$ = −43.0 MeV
$V_{T=5/2}$ = −46.5 MeV
Int. norm. ⁸He+p (a.u.)
E (⁸He+p) (MeV)
⁸He-p
Phase shift δ (deg)
E (⁸He+p) (MeV)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)
E (⁸He+p) (MeV)



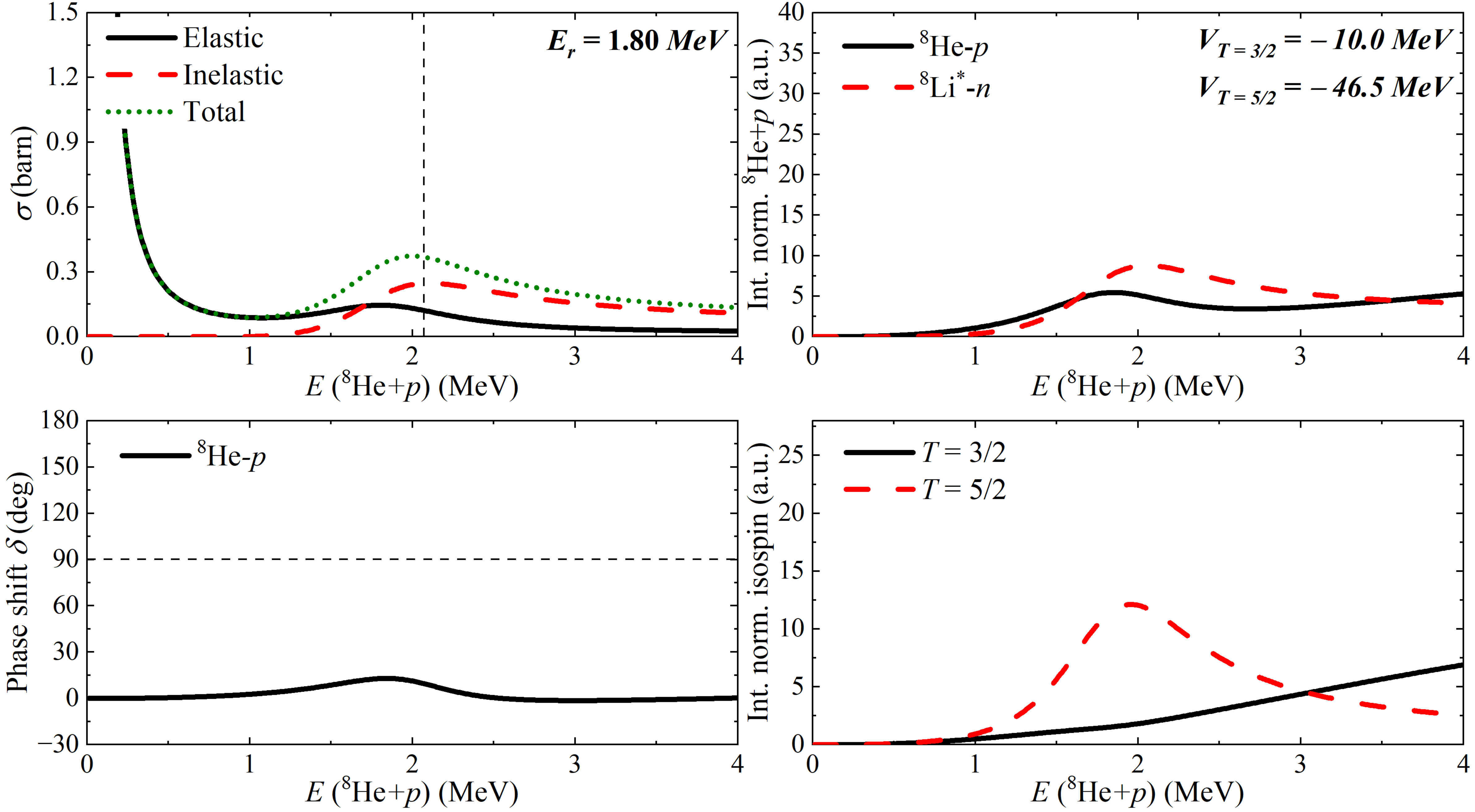
Elastic
Inelastic
Total
E_r = 3.25 MeV
σ (barn)
E (⁸He+p) (MeV)
⁸He-p
⁸Li*-n
$V_{T=3/2}$ = −40.0 MeV
$V_{T=5/2}$ = −46.5 MeV
Int. norm. ⁸He+p (a.u.)
E (⁸He+p) (MeV)
⁸He-p
Phase shift δ (deg)
E (⁸He+p) (MeV)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)
E (⁸He+p) (MeV)

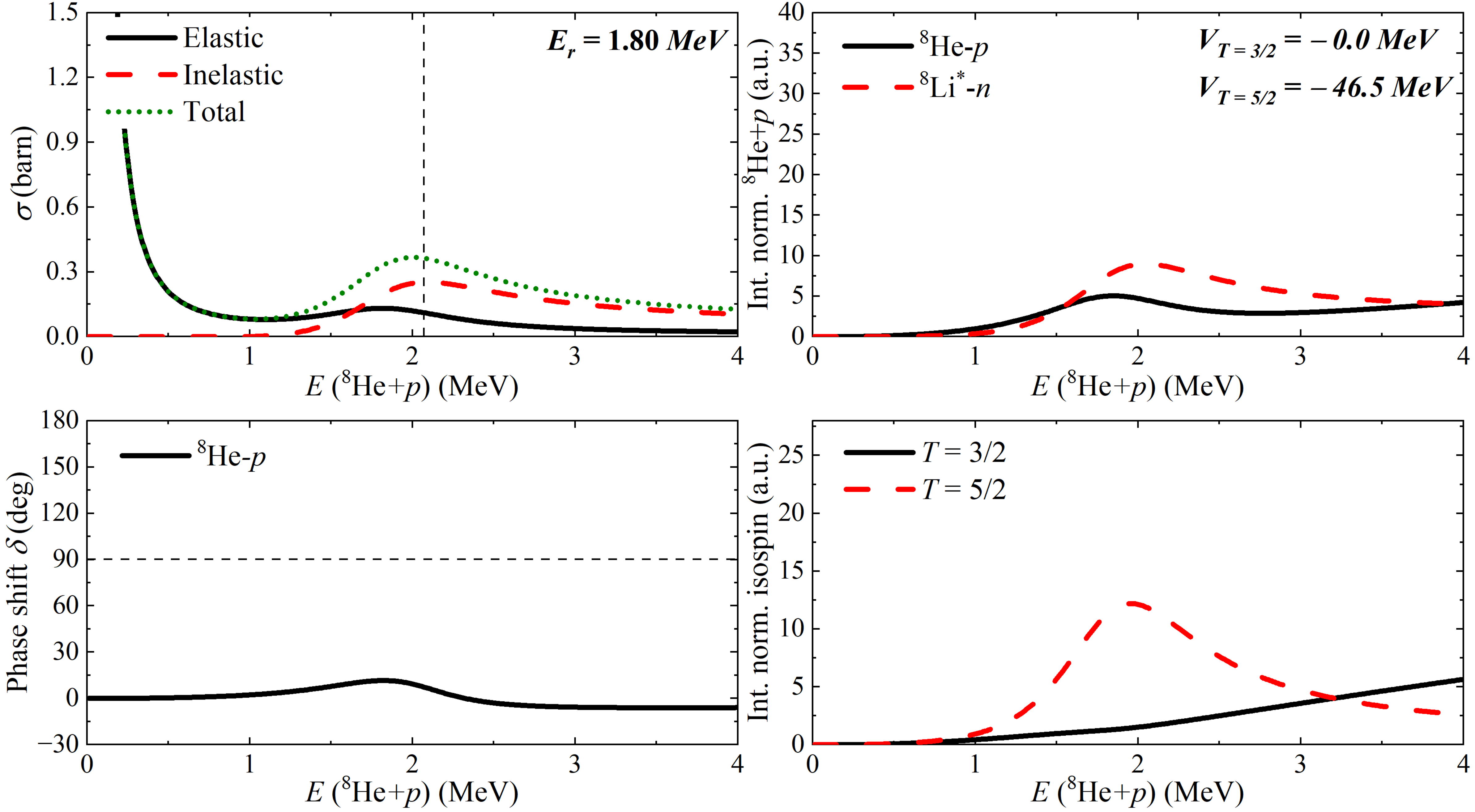


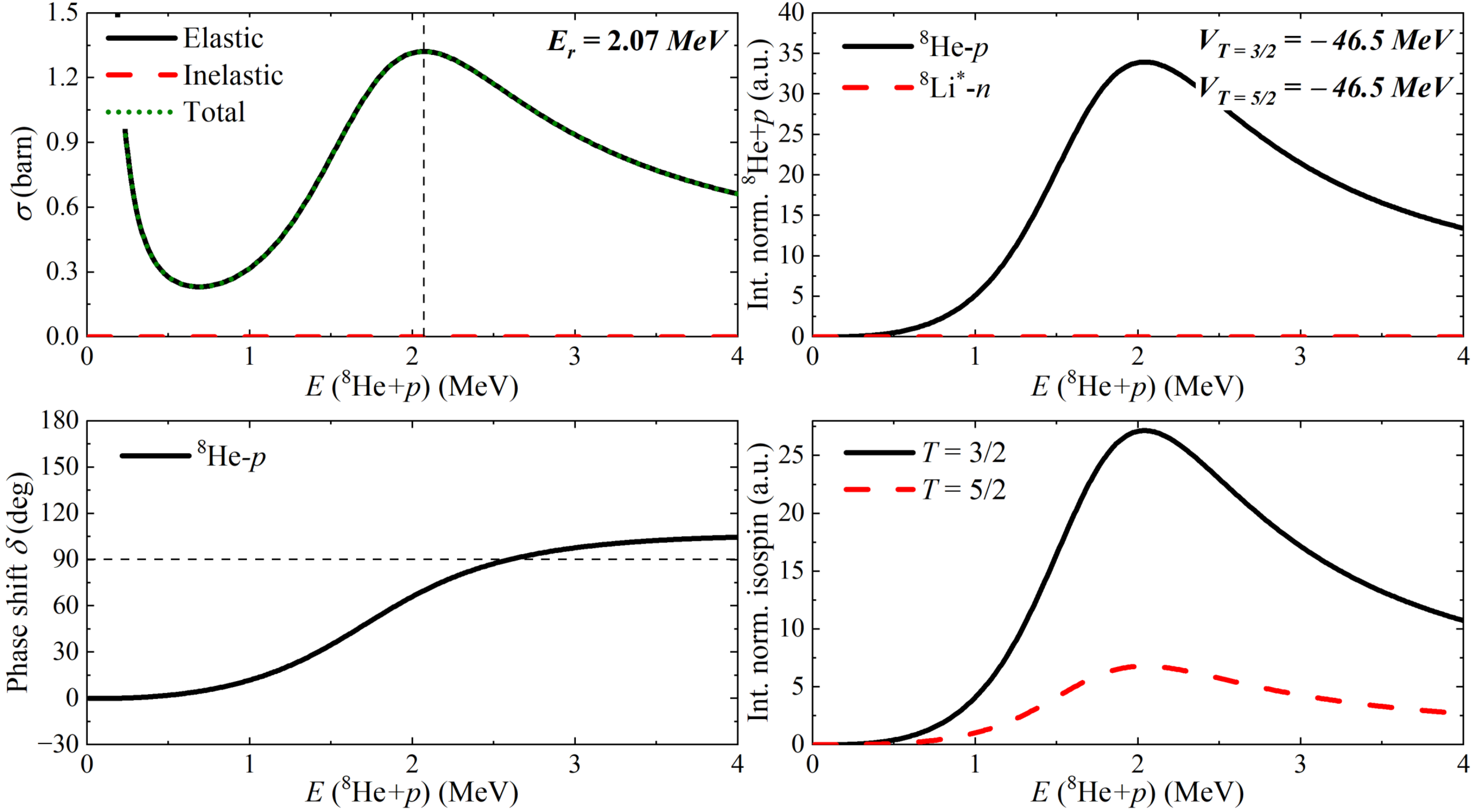
Elastic
Inelastic
Total
E_r = 1.85 MeV
σ (barn)
E (⁸He+p) (MeV)
⁸He-p
⁸Li*-n
$V_{T=3/2}$ = −35.0 MeV
$V_{T=5/2}$ = −46.5 MeV
Int. norm. ⁸He+p (a.u.)
E (⁸He+p) (MeV)
⁸He-p
Phase shift δ (deg)
E (⁸He+p) (MeV)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)
E (⁸He+p) (MeV)



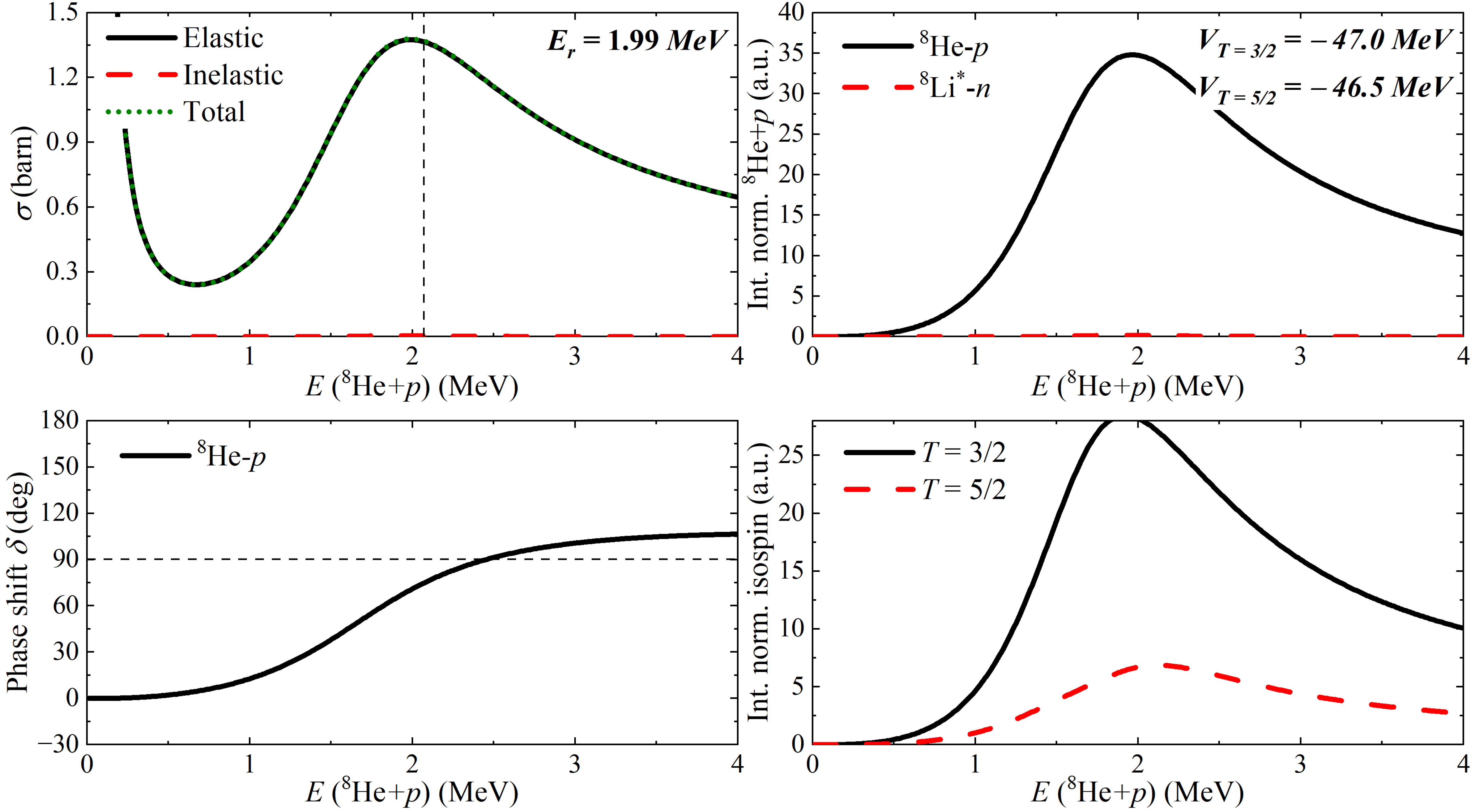
Elastic
Inelastic
Total
E_r = 1.80 MeV
σ (barn)
E (8He+p) (MeV)
8He-p
8Li*-n
V_T = 3/2 = −25.0 MeV
V_T = 5/2 = −46.5 MeV
Int. norm. 8He+p (a.u.)
8He-p
Phase shift δ (deg)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)


Elastic
Inelastic
Total
E_r = 1.80 MeV
σ (barn)
E (^{8}He+p) (MeV)
^{8}He-p
^{8}Li*-n
$V_{T=3/2}$ = −10.0 MeV
$V_{T=5/2}$ = −46.5 MeV
Int. norm. ^{8}He+p (a.u.)
Phase shift δ (deg)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)

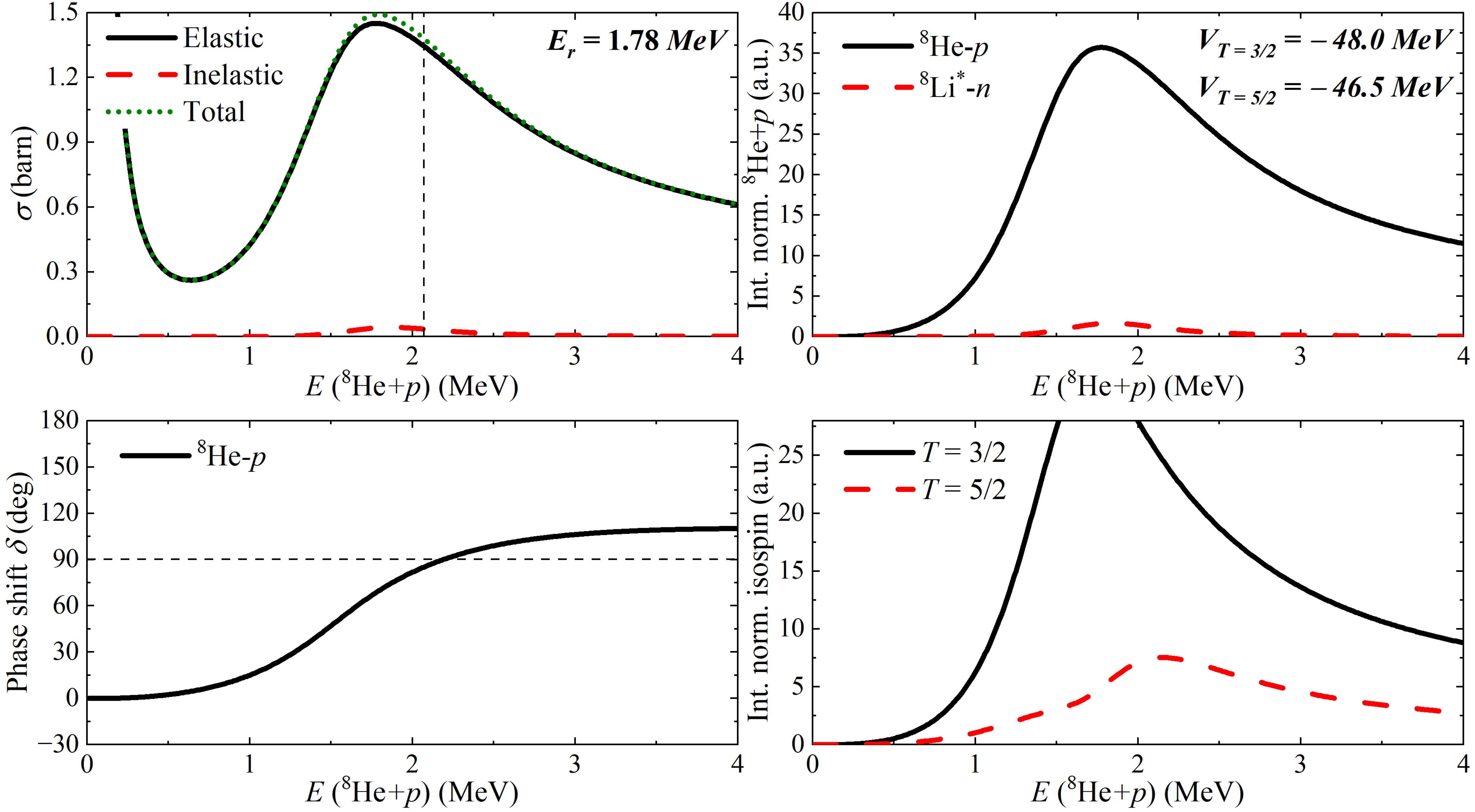

Elastic
Inelastic
Total
E_r = 1.80 MeV
σ (barn)
E (^{8}He+p) (MeV)
^{8}He-p
^{8}Li*-n
$V_{T=3/2}$ = −0.0 MeV
$V_{T=5/2}$ = −46.5 MeV
Int. norm. ^{8}He+p (a.u.)
Phase shift δ (deg)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)

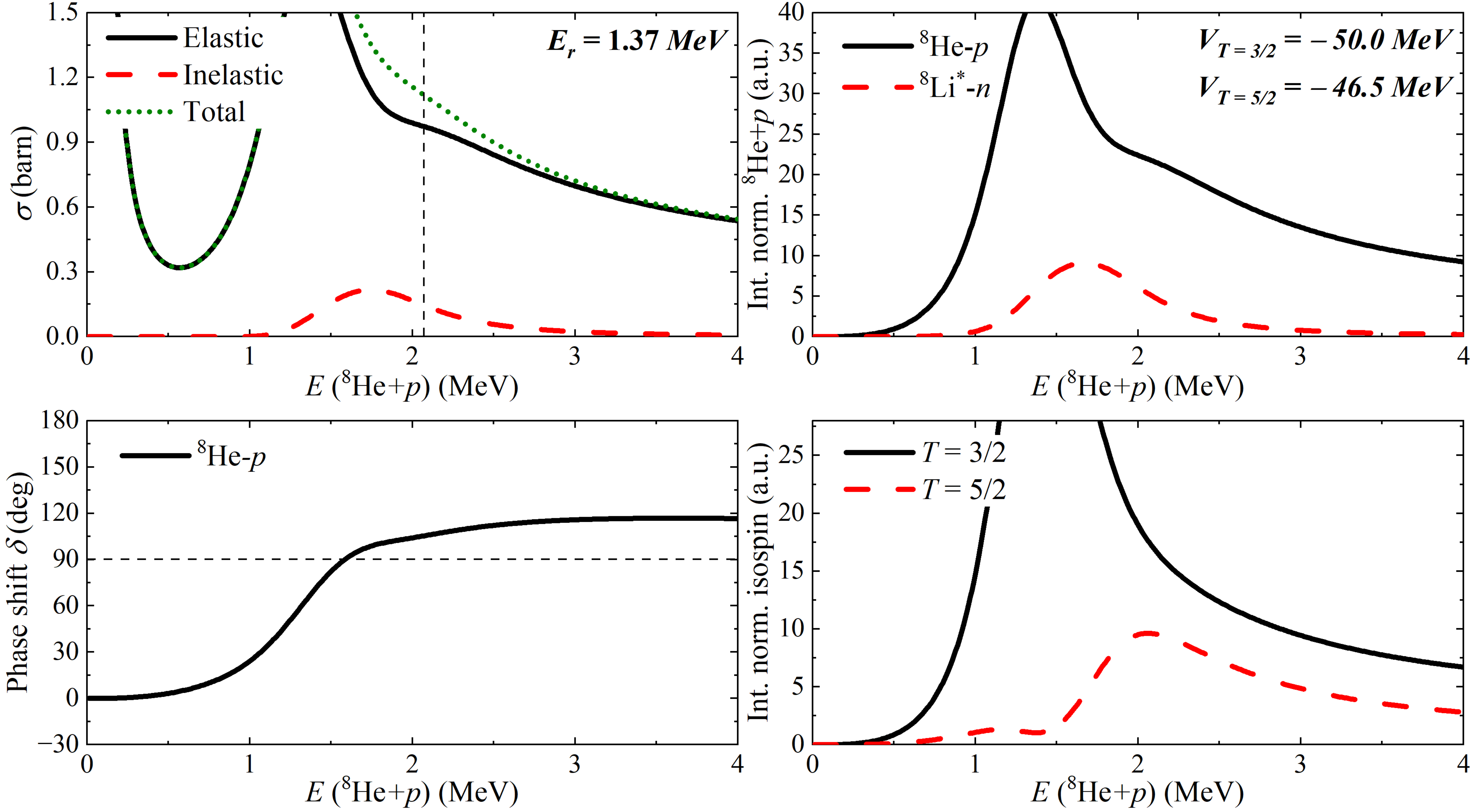


Elastic
Inelastic
Total
E_r = 2.07 MeV
σ (barn)
1.5
1.2
0.9
0.6
0.3
0.0
0
1
2
3
4
E (^{8}He+p) (MeV)
^{8}He-p
^{8}Li*-n
$V_{T=3/2}$ = −46.5 MeV
$V_{T=5/2}$ = −46.5 MeV
Int. norm. ^{8}He+p (a.u.)
40
35
30
25
20
15
10
5
0
Phase shift δ (deg)
180
150
120
90
60
30
−30
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)

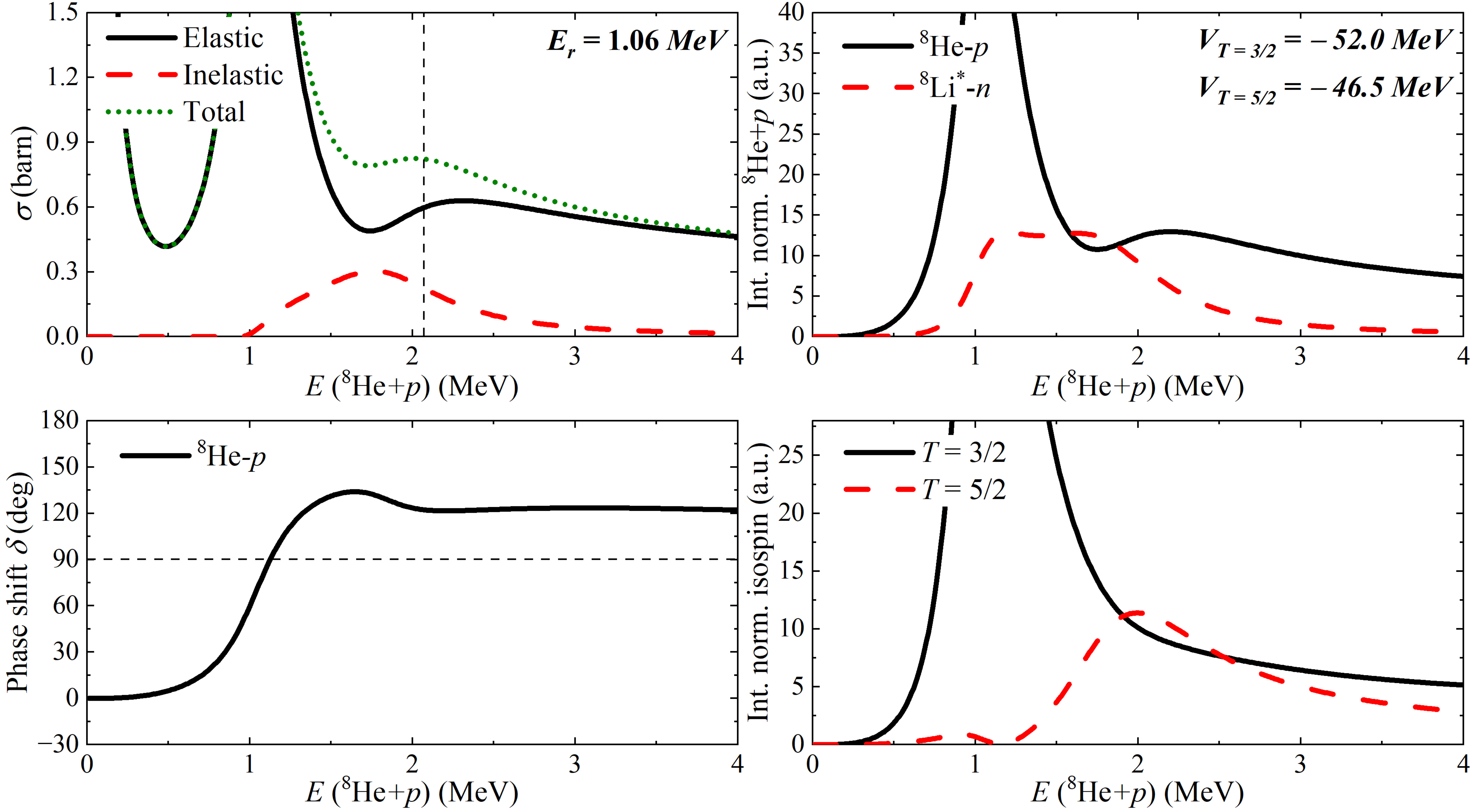


Elastic
Inelastic
Total
E_r = 1.99 MeV
σ (barn)
E (⁸He+p) (MeV)
⁸He-p
⁸Li*-n
$V_{T=3/2}$ = −47.0 MeV
$V_{T=5/2}$ = −46.5 MeV
Int. norm. ⁸He+p (a.u.)
Phase shift δ (deg)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)

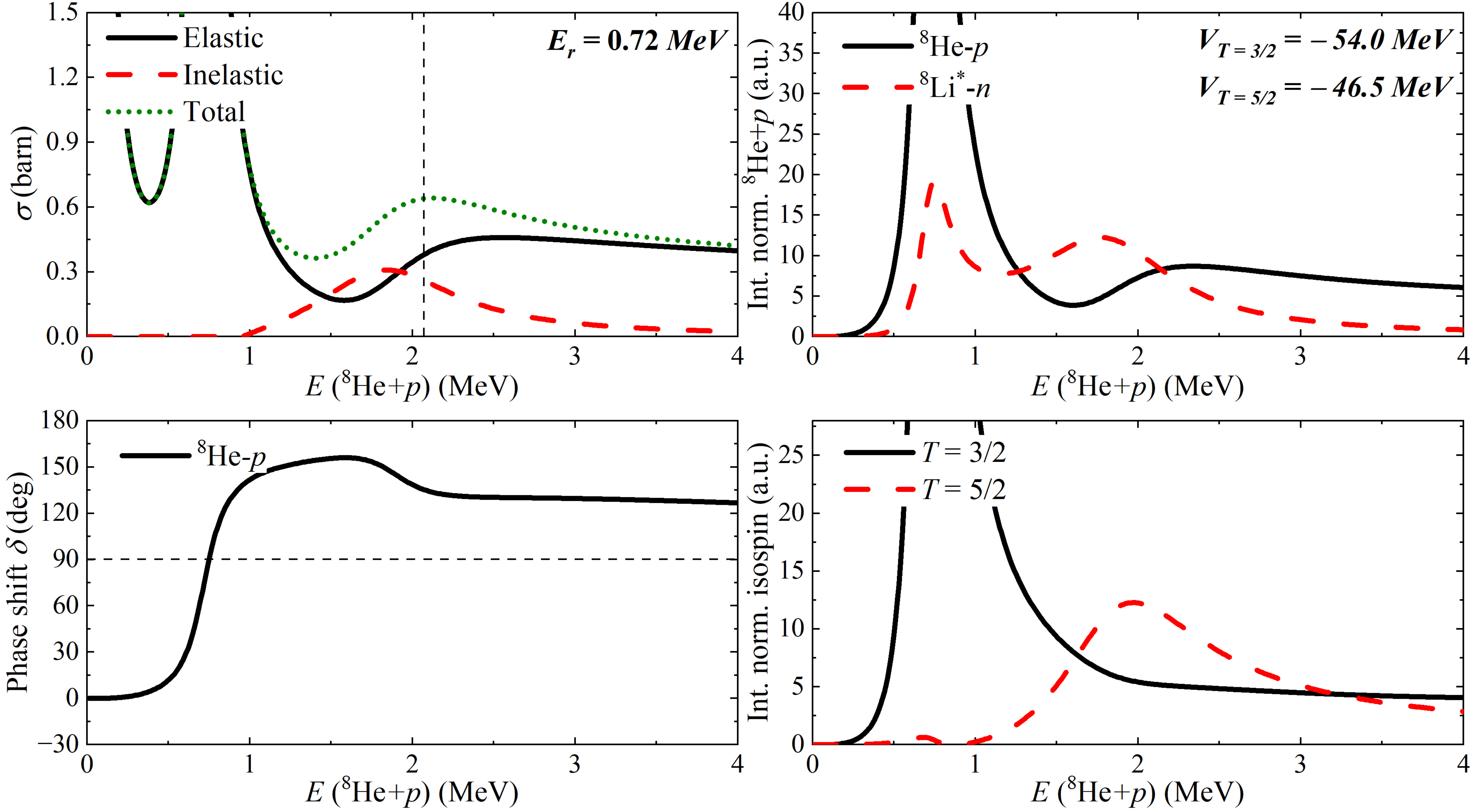

Elastic
Inelastic
Total
E_r = 1.78 MeV
σ (barn)
E (^{8}He+p) (MeV)
^{8}He-p
^{8}Li*-n
$V_{T=3/2}$ = −48.0 MeV
$V_{T=5/2}$ = −46.5 MeV
Int. norm. ^{8}He+p (a.u.)
Phase shift δ (deg)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)



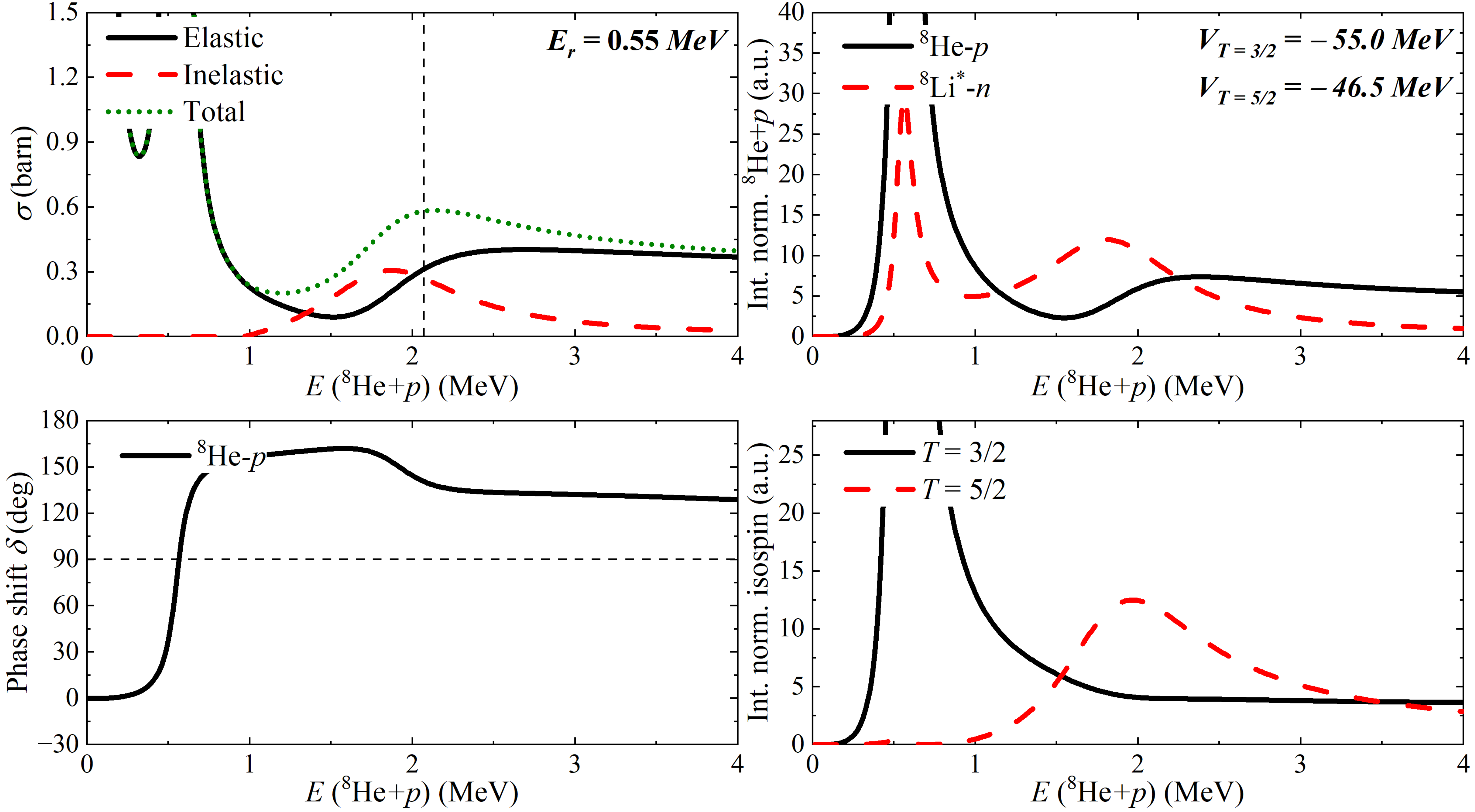
Elastic
Inelastic
Total
E_r = 1.37 MeV
σ (barn)
E (8He+p) (MeV)
8He-p
8Li*-n
V_T = 3/2 = − 50.0 MeV
V_T = 5/2 = − 46.5 MeV
Int. norm. 8He+p (a.u.)
E (8He+p) (MeV)
8He-p
Phase shift δ (deg)
E (8He+p) (MeV)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)
E (8He+p) (MeV)



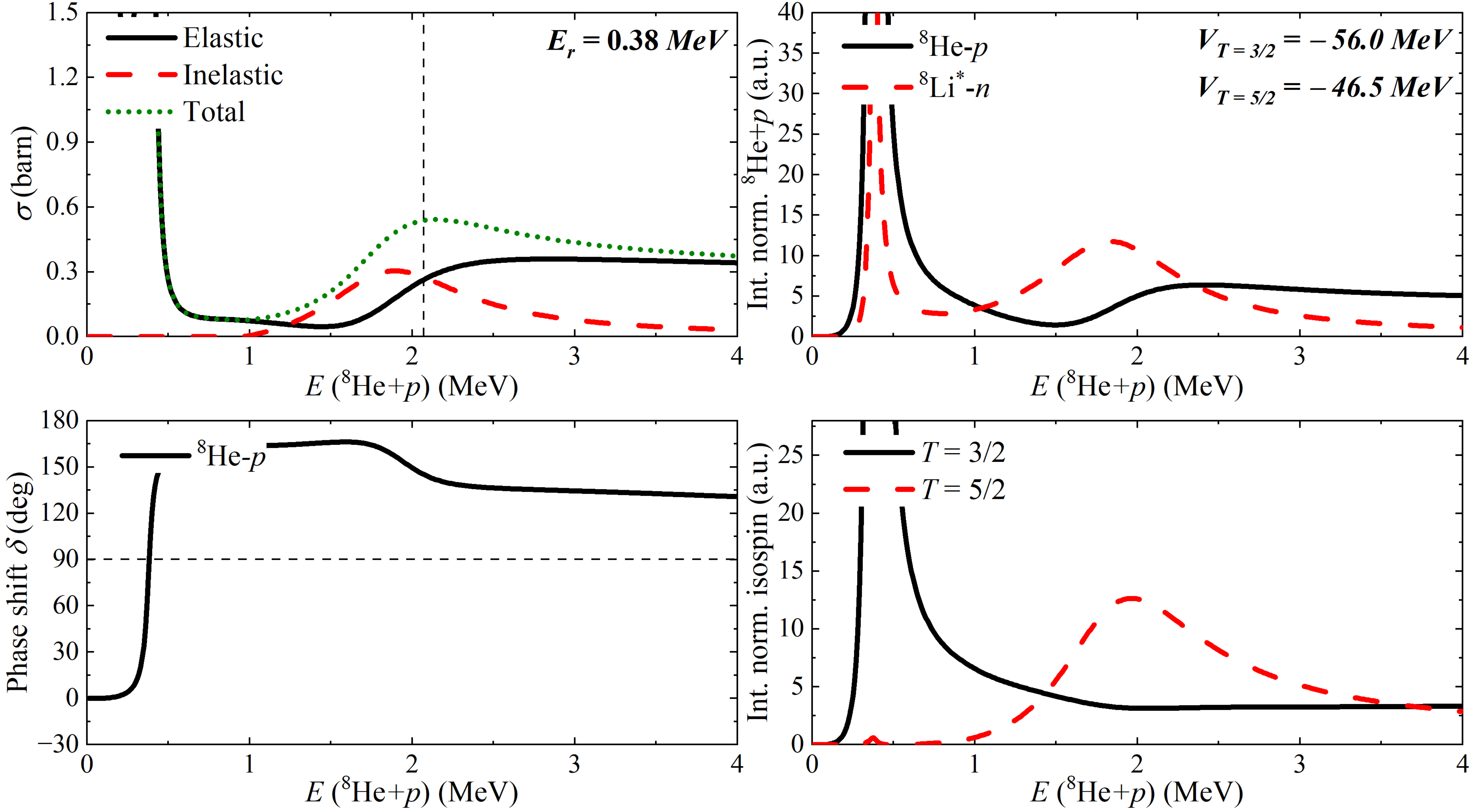
1.5
1.2
0.9
0.6
0.3
0.0
σ (barn)
Elastic
Inelastic
Total
E_r = 1.06 MeV
0
1
2
3
4
E (8He+p) (MeV)
40
35
30
25
20
15
10
5
0
Int. norm. 8He+p (a.u.)
8He-p
8Li*-n
V_T = 3/2 = – 52.0 MeV
V_T = 5/2 = – 46.5 MeV
E (8He+p) (MeV)
180
150
120
90
60
30
0
–30
Phase shift δ (deg)
8He-p
E (8He+p) (MeV)
25
20
15
10
5
0
Int. norm. isospin (a.u.)
T = 3/2
T = 5/2
E (8He+p) (MeV)



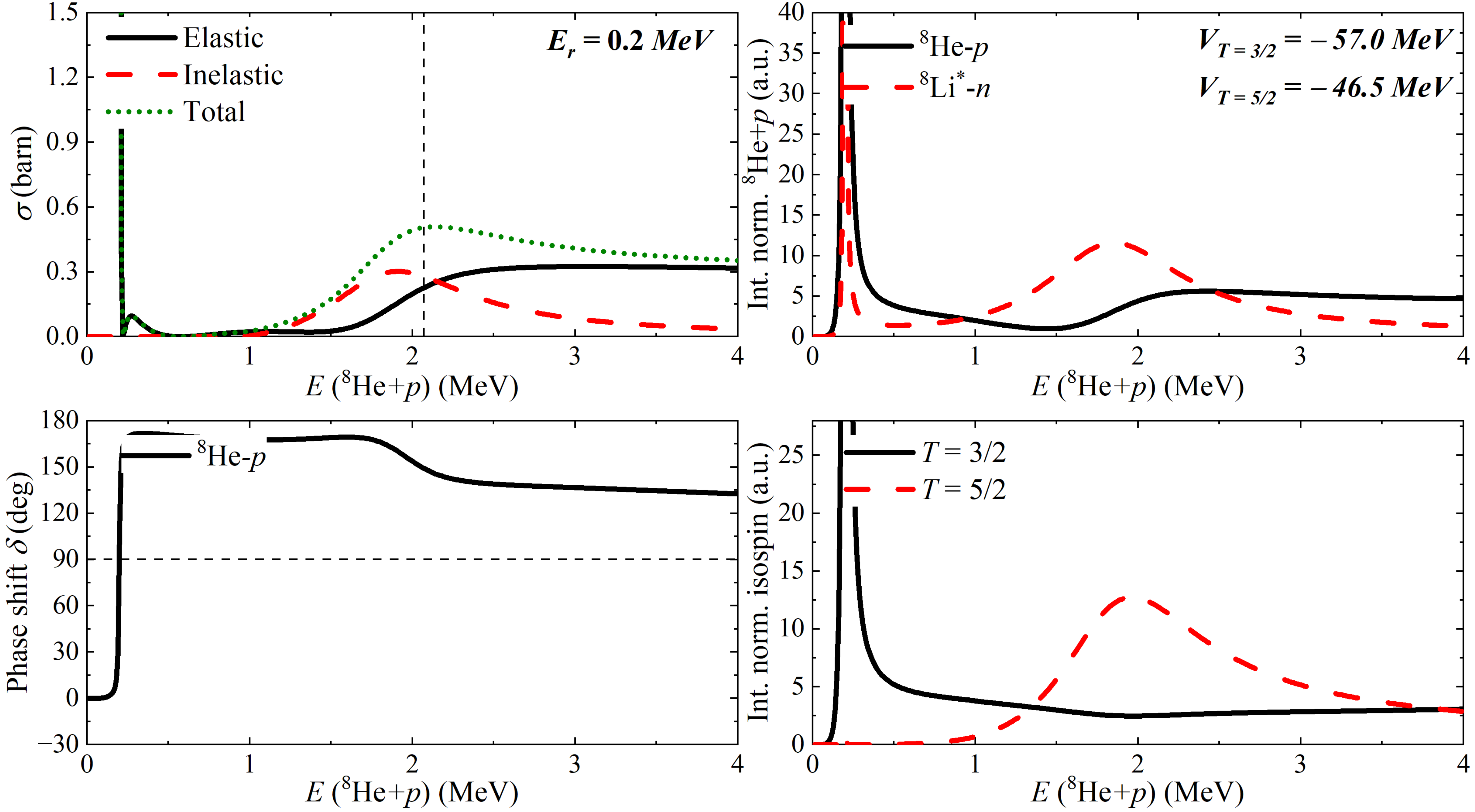
Elastic
Inelastic
Total
E_r = 0.72 MeV
σ (barn)
E (^{8}He+p) (MeV)
^{8}He-p
^{8}Li*-n
$V_{T=3/2}$ = – 54.0 MeV
$V_{T=5/2}$ = – 46.5 MeV
Int. norm. ^{8}He+p (a.u.)
E (^{8}He+p) (MeV)
^{8}He-p
Phase shift δ (deg)
E (^{8}He+p) (MeV)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)
E (^{8}He+p) (MeV)



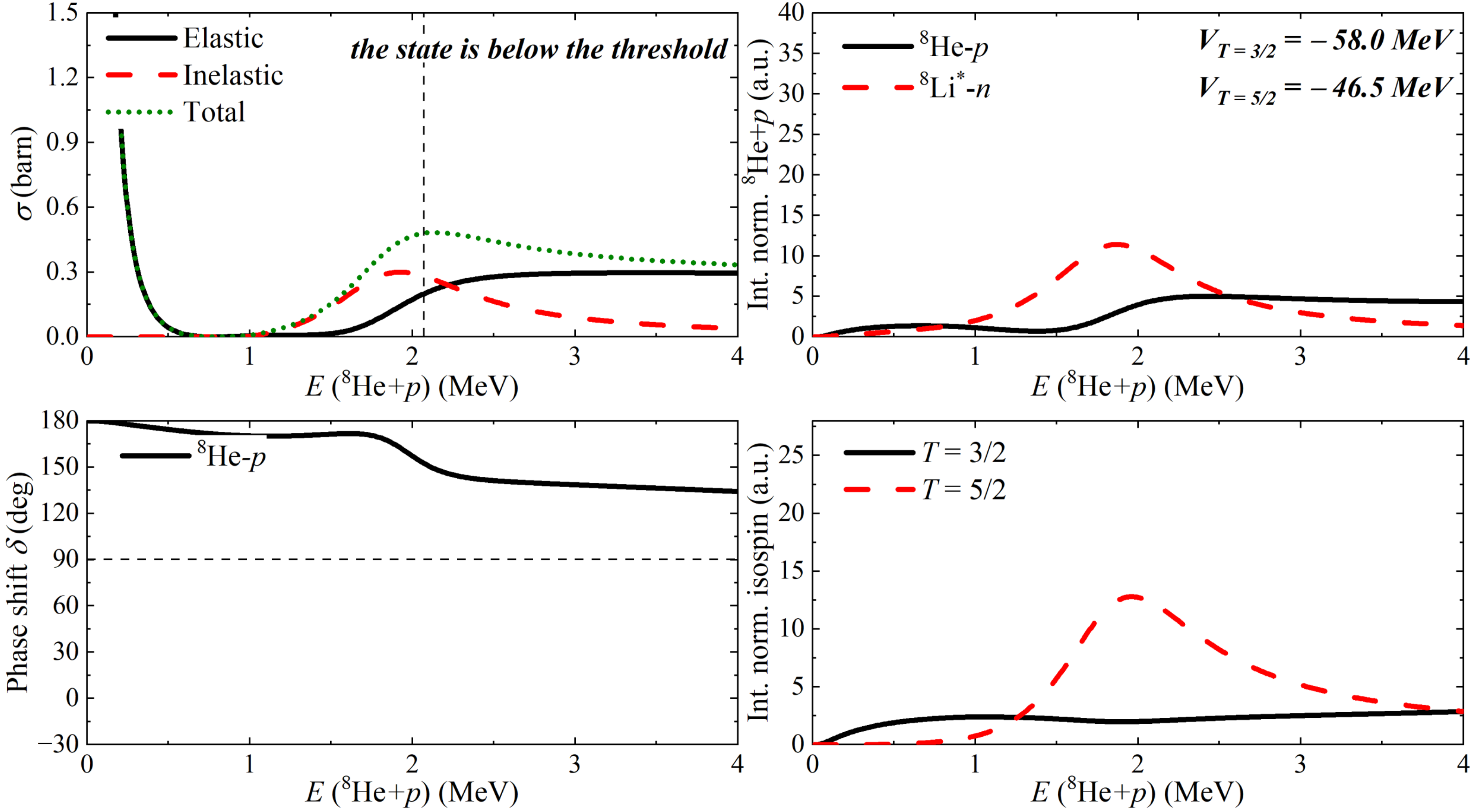
Elastic
Inelastic
Total
E_r = 0.55 MeV
σ (barn)
E (^{8}He+p) (MeV)
^{8}He-p
^{8}Li*-n
$V_{T=3/2}$ = −55.0 MeV
$V_{T=5/2}$ = −46.5 MeV
Int. norm. ^{8}He+p (a.u.)
E (^{8}He+p) (MeV)
^{8}He-p
Phase shift δ (deg)
E (^{8}He+p) (MeV)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)
E (^{8}He+p) (MeV)

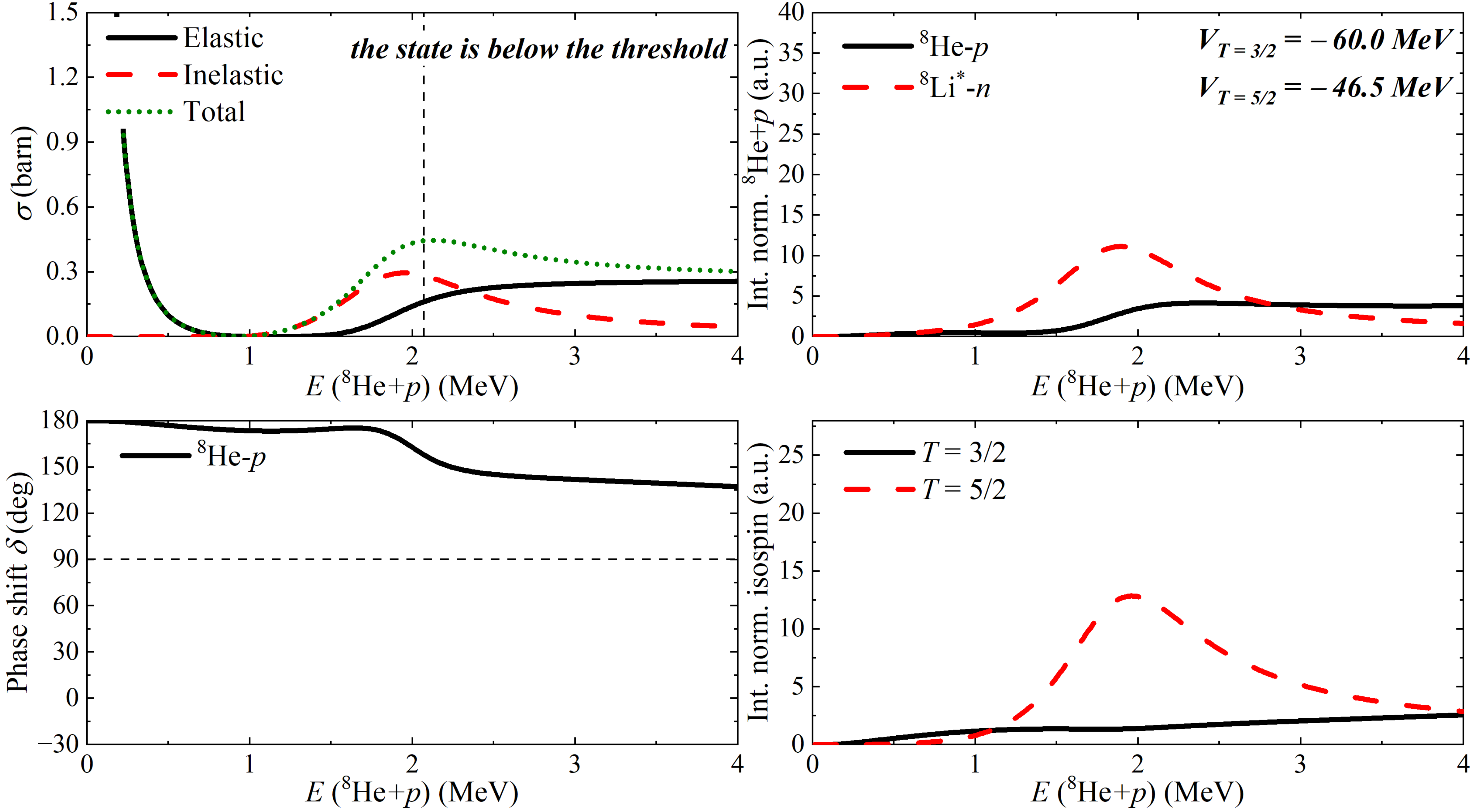


Elastic
Inelastic
Total
E_r = 0.38 MeV
σ (barn)
E (8He+p) (MeV)
8He-p
8Li*-n
V_T = 3/2 = – 56.0 MeV
V_T = 5/2 = – 46.5 MeV
Int. norm. 8He+p (a.u.)
E (8He+p) (MeV)
8He-p
Phase shift δ (deg)
E (8He+p) (MeV)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)
E (8He+p) (MeV)

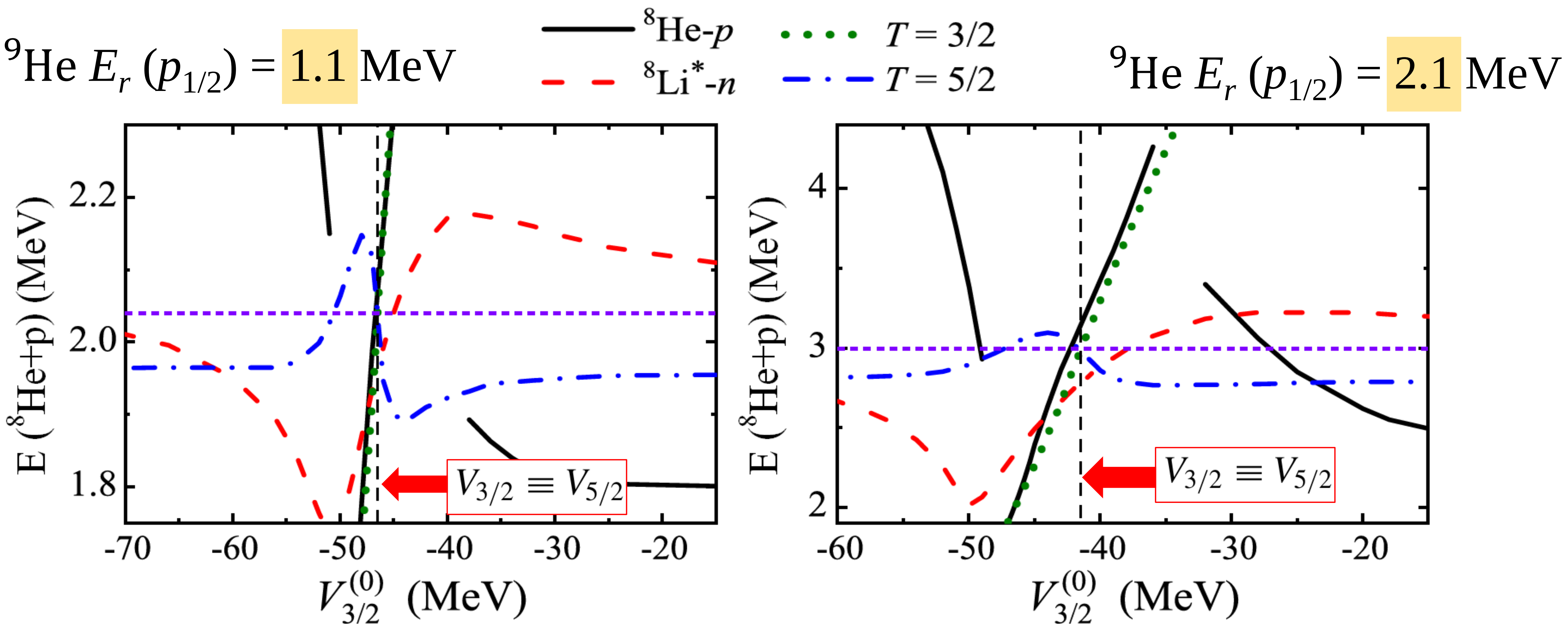


Elastic
Inelastic
Total
E_r = 0.2 MeV
σ (barn)
E (⁸He+p) (MeV)
⁸He-p
⁸Li*-n
$V_{T=3/2}$ = −57.0 MeV
$V_{T=5/2}$ = −46.5 MeV
Int. norm. ⁸He+p (a.u.)
E (⁸He+p) (MeV)
⁸He-p
Phase shift δ (deg)
E (⁸He+p) (MeV)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)
E (⁸He+p) (MeV)


Elastic
Inelastic
Total
the state is below the threshold
σ (barn)
E (8He+p) (MeV)
8He-p
8Li*-n
V T = 3/2 = – 58.0 MeV
V T = 5/2 = – 46.5 MeV
Int. norm. 8He+p (a.u.)
E (8He+p) (MeV)
8He-p
Phase shift δ (deg)
E (8He+p) (MeV)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)
E (8He+p) (MeV)



Elastic
Inelastic
Total
the state is below the threshold
σ (barn)
E (8He+p) (MeV)
8He-p
8Li*-n
V T = 3/2 = – 60.0 MeV
V T = 5/2 = – 46.5 MeV
Int. norm. 8He+p (a.u.)
Phase shift δ (deg)
T = 3/2
T = 5/2
Int. norm. isospin (a.u.)

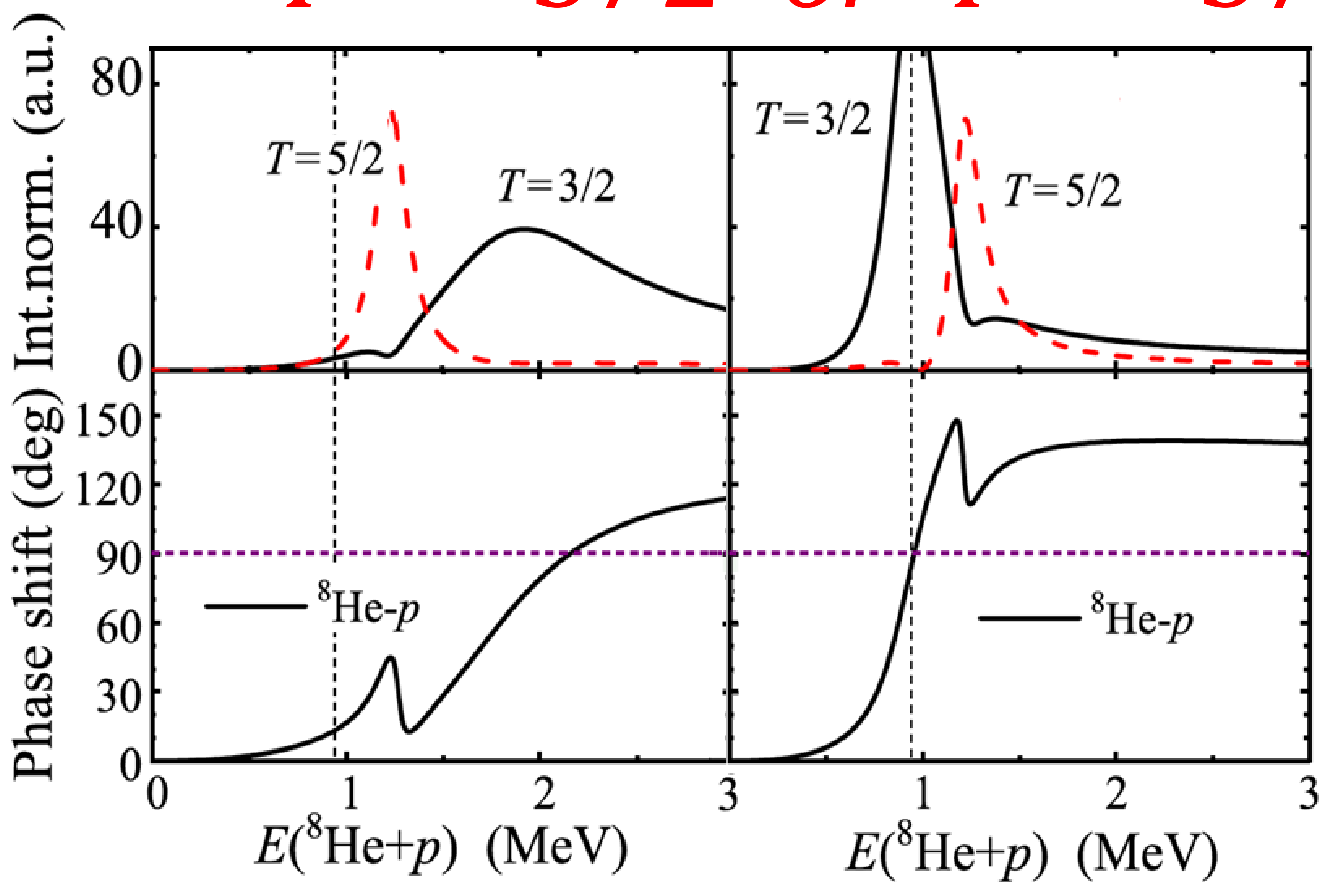


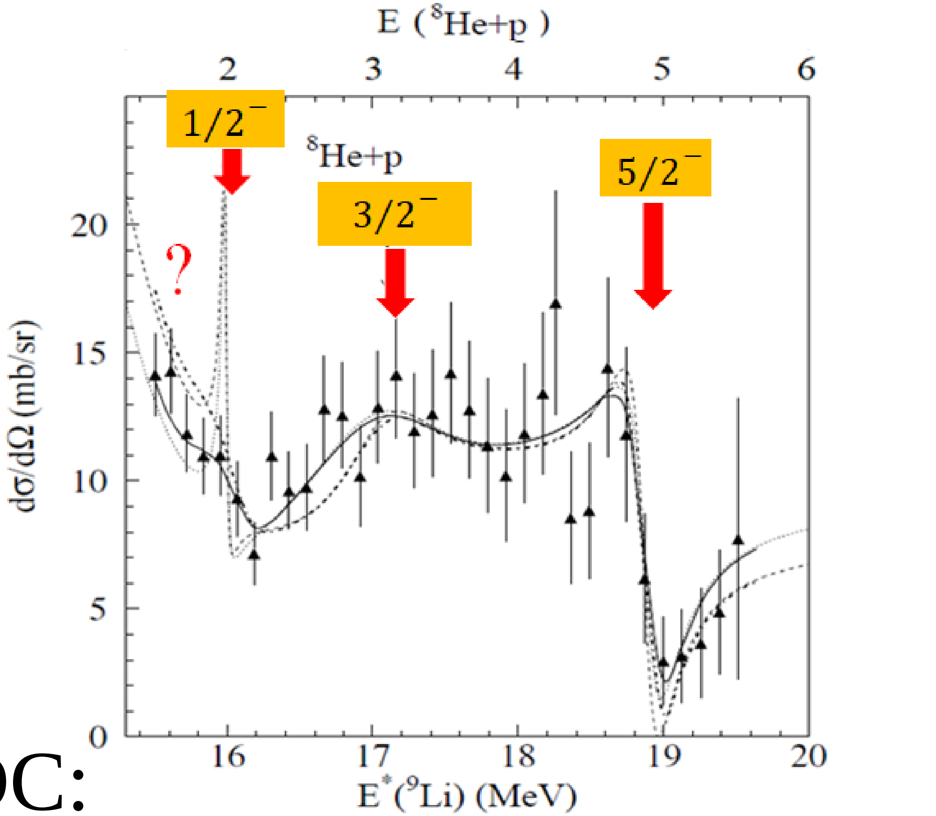
- The scale of energy variation of different peaks with a variation of $V_{3/2}$ interaction is of the order of Γ/2. This is a large effect for broad states, which cannot be disregarded.

- Only single type of data **is not sufficient** to understand the actual T = 5/2 position.
- **Only the simultaneous studies** of the ^{8}He+p and ^{8}Li*+n channels may provide sufficient evidence to fix the T =5/2 states in the ^{8}He+n system.

$T = 5/2$ or $T = 3/2$?

G. V. Rogachev et al., Phys. Rev. C 67, 041603 (2003).

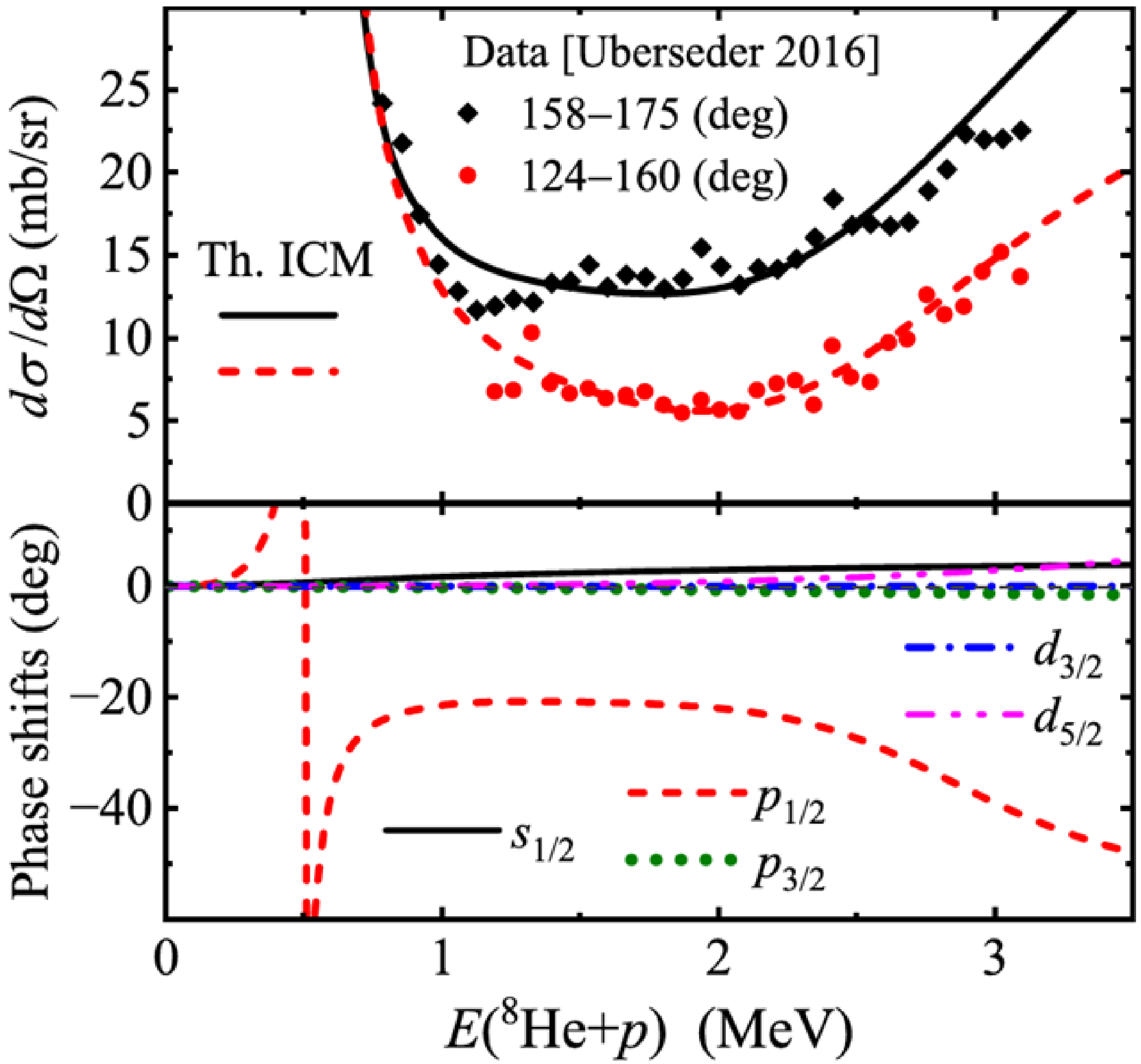




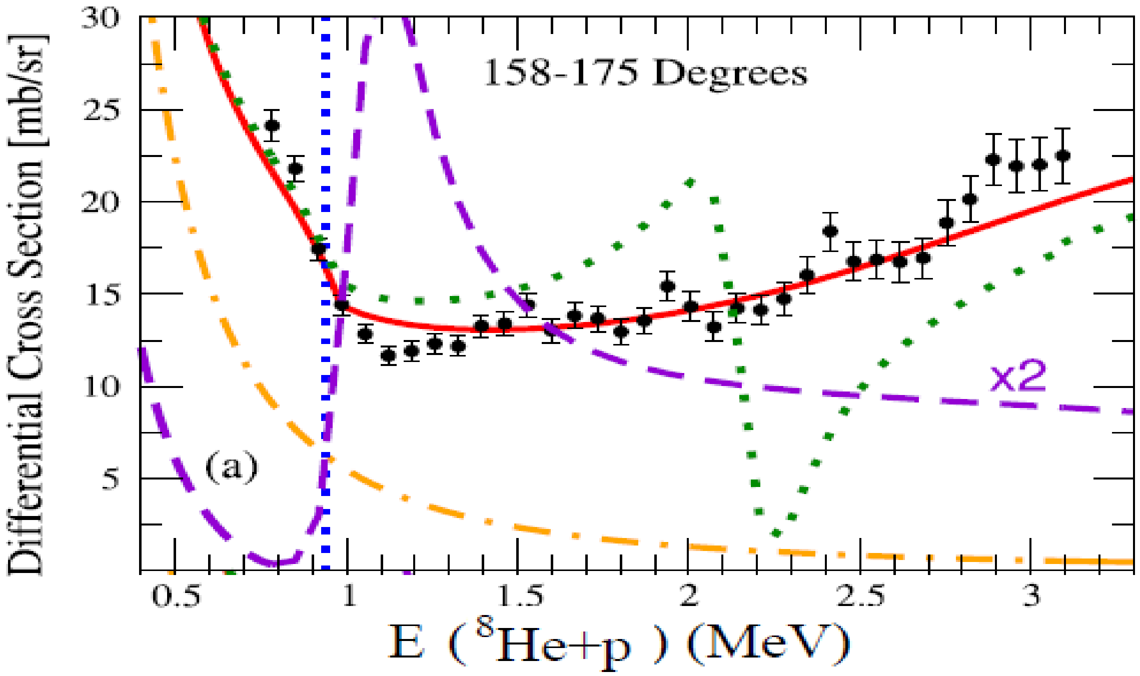
NNDC:

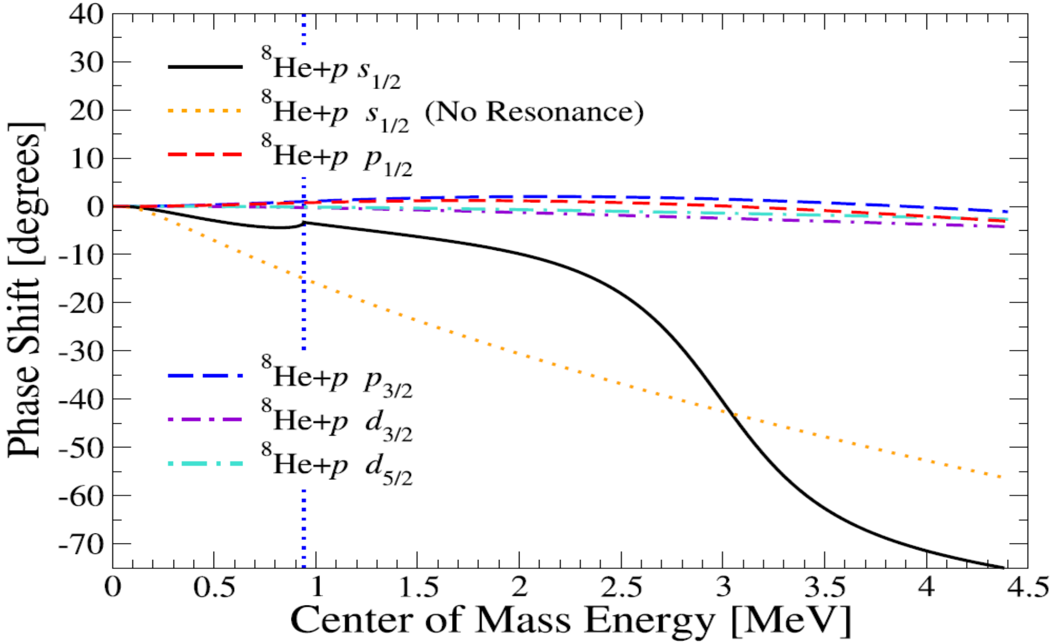
E(level) (keV)	XREF	J^π(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)
0.0	BCDEF	3/2−	178.3 ms 4 % β^- = 100 % β^-n = 50.8 2		
2691 5	BCD F	(1/2−)	% IT = 100	2691 5	100
4301 12	B FG		88 keV 25 % n ≤ 100		
5380 60	B		0.6 MeV 1		
6430 15	B EF	GE 9/2	40 keV 20		
16.0E3 1	A		< 100 keV % p ≤ 100		
17.1E3 2	A		0.8 MeV 3 % p ≤ 100		
18.9E3 1	A		0.24 MeV 10 % p ≤ 100		

- Whatever state is higher in energy (the T = 3/2 or the T = 5/2) the T = 3/2 state demonstrates the “classical” resonant behavior, with the phase shift passing π/2, while at the T = 5/2 resonance energy, only a relatively small “wiggle” in the phase shift is observed.
- Resonant properties were likely misinterpreted, and the states declared as T = 5/2 due to the phase shifts should be really the T = 3/2 states



E. Uberseder et al., Phys. Lett. B 754, 323 (2016).





Data [Uberseder 2016] can be interpreted within ICM in an alternative and more "orthodox" way:

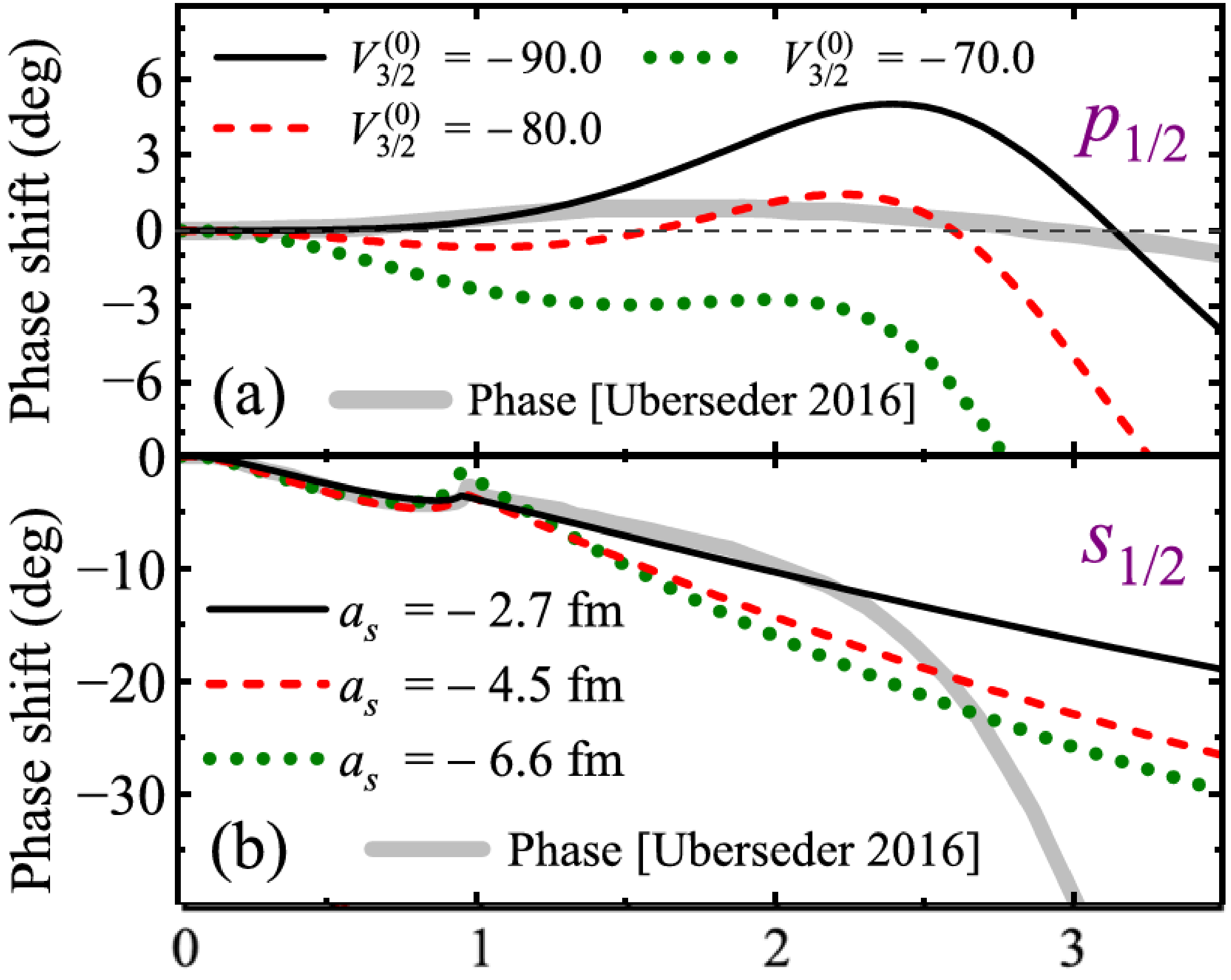
1) weak attraction in the $1/2^+$ channel
2) single-particle $1/2^-$ resonance at E_r = 2.3MeV
3) $5/2^+$ resonance at E_r = 4.7 MeV

Conclusions

- The resonance scattering of exotic nuclide on a thick target $^{A}Z + p$ in inverse kinematics can be used to infer the properties of the low-energy neutron scattering $^{A}Z + n$ on this nuclide by assuming the isobaric symmetry. However, for the relatively broad states and the ^{A}Z subsystem with nonzero isospin, the effects of the isospin mixing and threshold effects are large and should be treated dynamically. This introduces additional uncertainty into the situation: for the $^{A}Z + n$ channel, we need only the nuclear cluster interaction with T_{max}, while for the $^{A}Z + p$ channel the $T_{max} - 1$ interaction should also be considered.
- It is thus demonstrated in this work that the results of the resonance proton scattering experiments aimed at the studies of the ”isobaric partner” neutron scattering channel may be interpreted in a very different way when isospin conservation is taken properly into account.

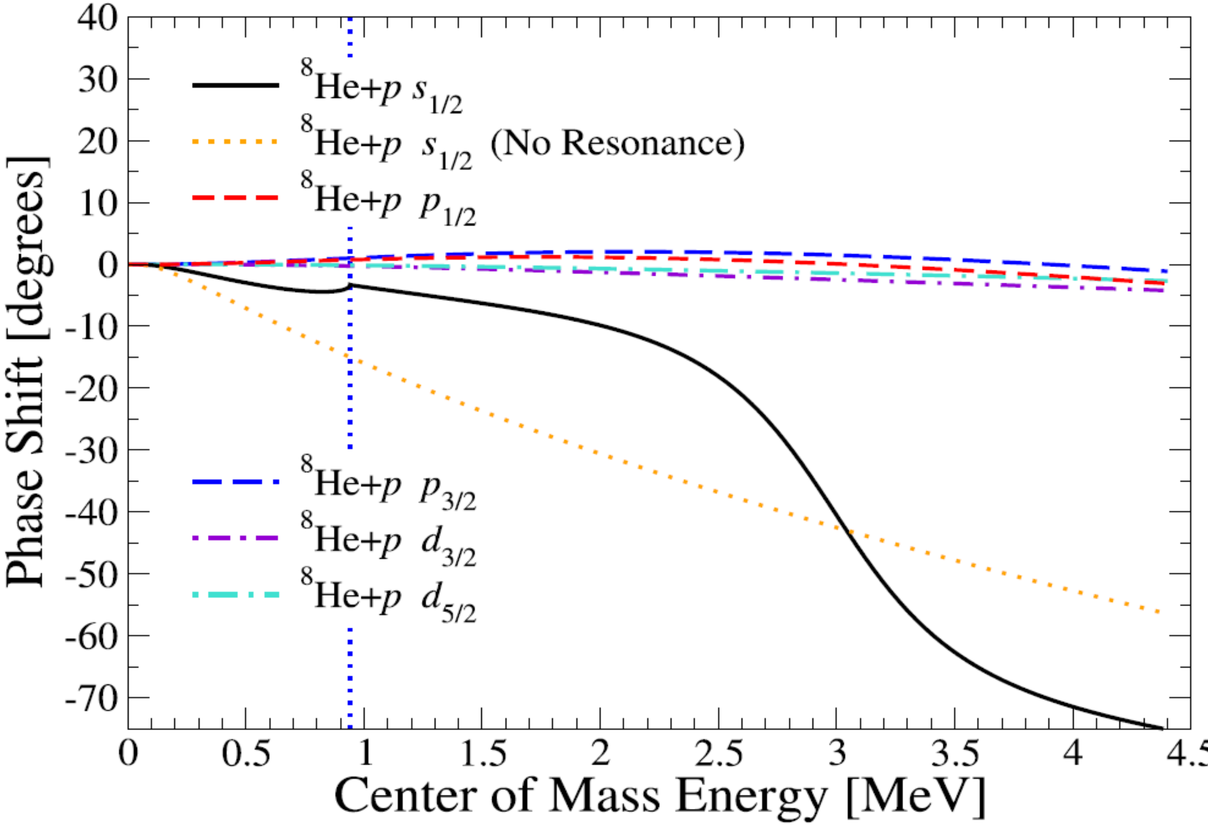
Thank you for your attention!

$1/2^-$ resonance
$E_r = 2.1$ MeV



$1/2^+$ resonance
$E_r \sim 3$ MeV

E. Uberseder et al., Phys. Lett. B 754, 323 (2016).



K. K. Seth et al., Phys. Rev. Lett. **58**, 1930 (1987).

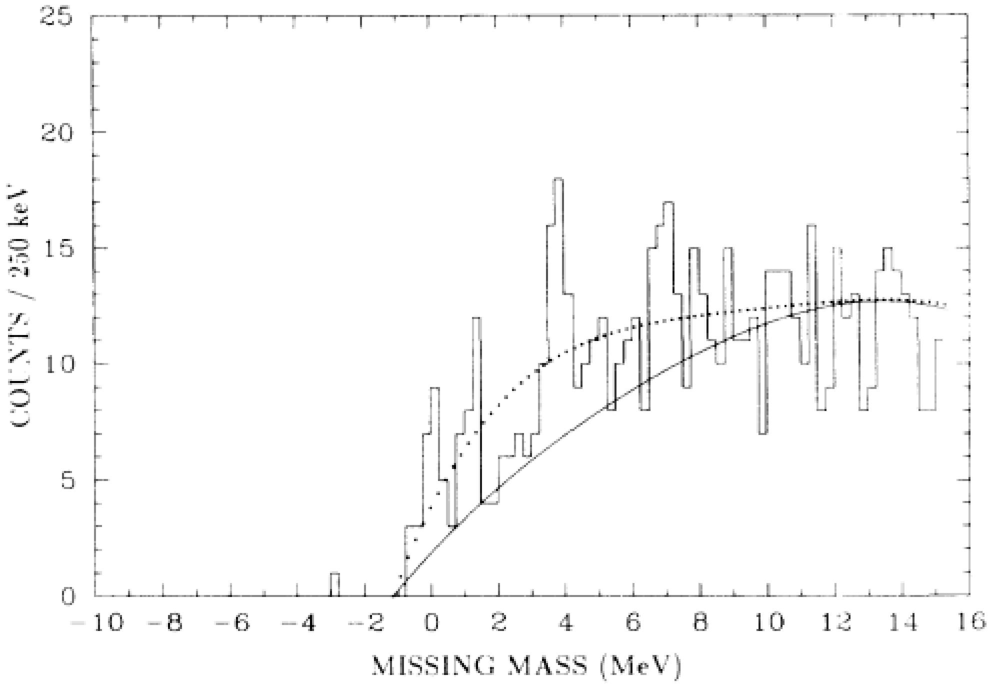
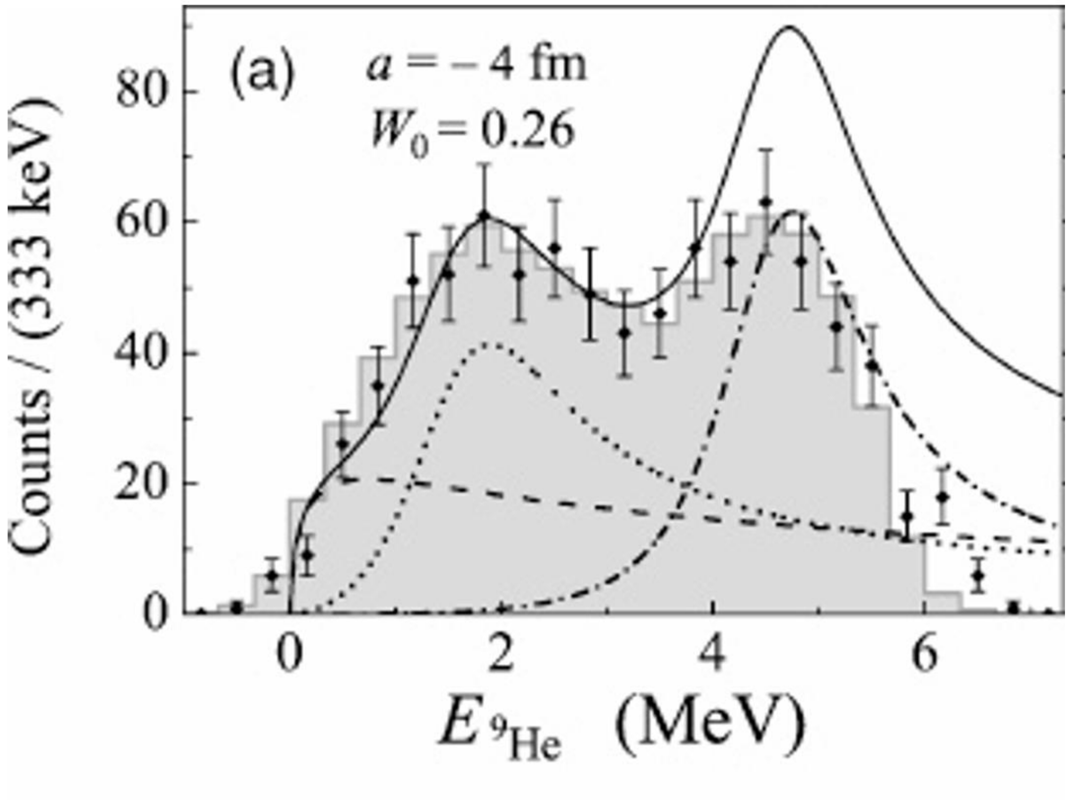
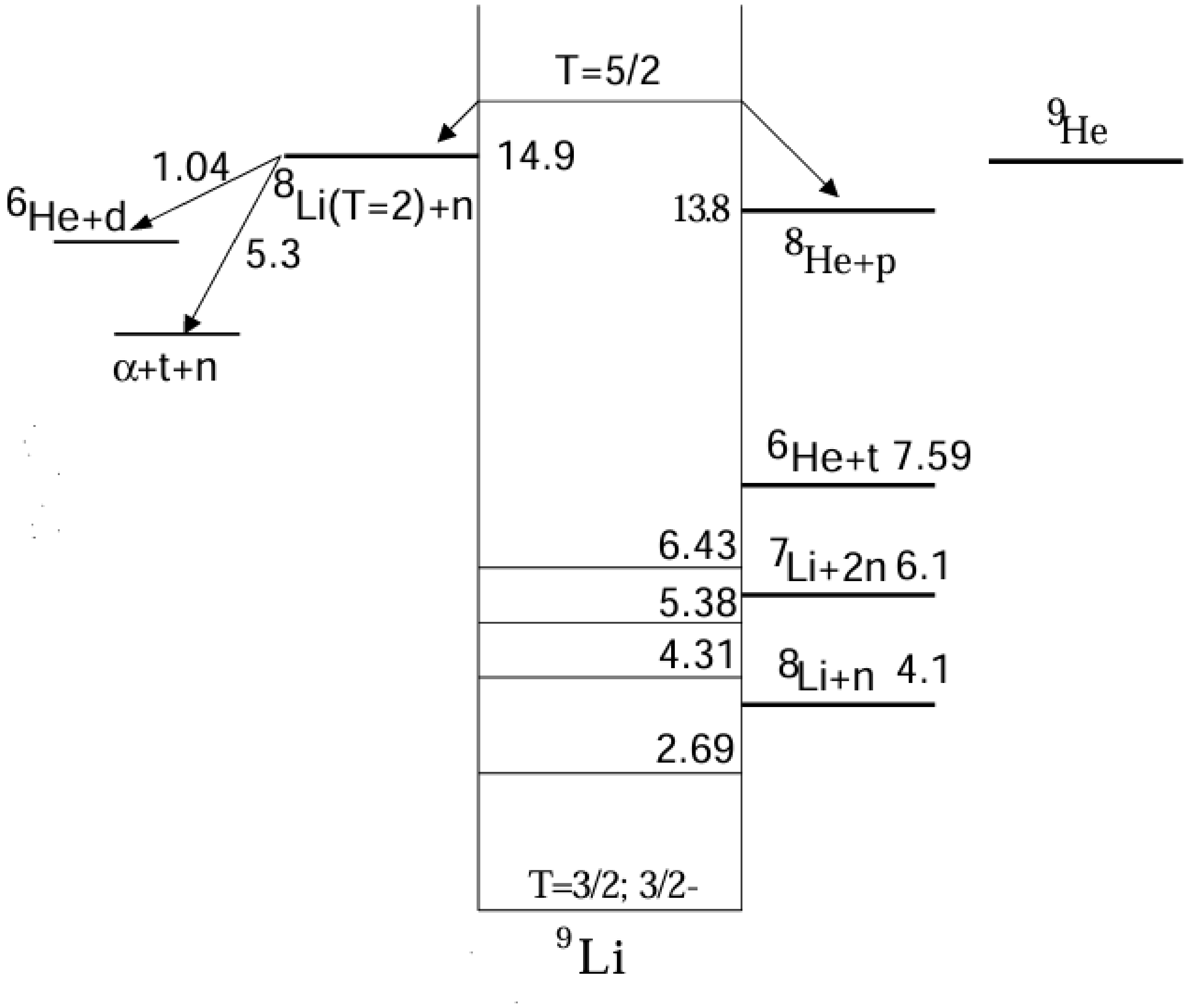
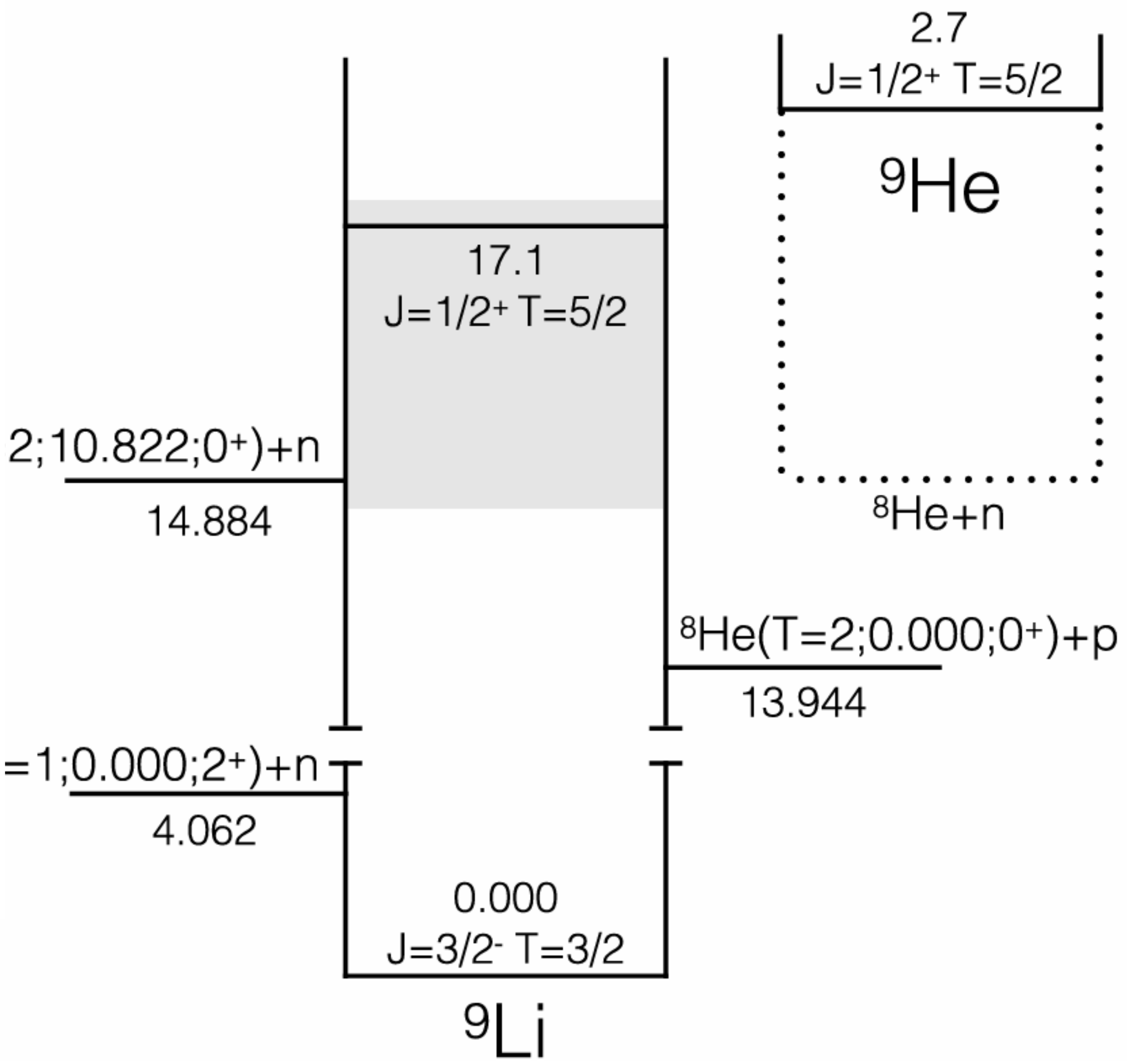


FIG. 1. Missing-mass spectrum for the reaction $^9Be(\pi^-, \pi^+)^9He$

M. S. Golovkov, L. V. Grigorenko et al., Phys.Rev.C76, 021605(R) (2007)




T=5/2
9He
14.9
1.04
8Li(T=2)+n
6He+d
5.3
α+t+n
13.8
8He+p
6He+t 7.59
6.43
7Li+2n 6.1
5.38
4.31
8Li+n 4.1
2.69
T=3/2; 3/2-
9Li


2.7
J=1/2+ T=5/2
9He
8He+n
17.1
J=1/2+ T=5/2
2;10.822;0+)+n
14.884
8He(T=2;0.000;0+)+p
13.944
=1;0.000;2+)+n
4.062
0.000
J=3/2- T=3/2
9Li